passing through an intensely cold medium ; the resulting water would travel forward with the same velocity which it had already acquired when in the state of steam; and if the various particles of water could by any means be gathered together into a continuous stream, they would be more than able to overcome and to force back into the boiler any opposing stream of water of the same size directed against them from the water-room of the boiler. Now the velocity of the condensed steam is so great that it possesses not only energy enough to re-enter the boiler in the face of an opposing stream of water of its own size, but it can also impart energy to a much larger mass of water, so that this larger mass can also enter the boiler. The injector is simply an instrument for allowing steam to rush from a boiler, and to suck up and mix with itself a stream of cold water, by which it is condensed, and to which it imparts so much of its own velocity that the combined mass of cold water and condensed steam enters into and feeds the boiler.

Fig. 184 shows an elementary form of such an injector. A is the section of a boiler, B a pipe leading from the steam space and terminating in a nozzle, C is the cold water pipe leading from the tank, and terminating in a hollow cone surrounding the steam nozzle. When the steam is turned on, and escapes from the lower edge E of the hollow cone, it creates a partial vacuum in the cone and in the pipe C. The water then rushes up the pipe and into the cone surrounding the nozzle, where it meets with the escaping steam,

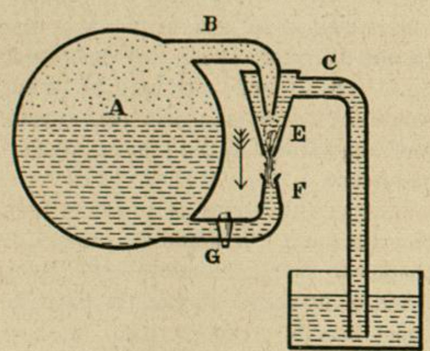

Fig. 184.

which it condenses. The particles of condensed steam, impinging on the water surrounding them, communicate their motion to the latter, and the combined mass is delivered at a high velocity into the feed-pipe F, and through the valve at G into the boiler. Such an injector, if properly proportioned, would work well for a fixed pressure of steam in the boiler, and for a fixed temperature of the feed water. In practice, however, these quantities vary, and injectors must be made to suit all such contingencies. For instance, when the pressure of the steam increases, the area of the opening in the steam nozzle must be increased, and *vice versâ*. There are very many forms of injectors. Fig. 185 illustrates one which is in common use in this country. The steam and water supply pipes, nozzle, and cone are rendered sufficiently clear by the drawing. The steam supply is varied by altering the position of the conical spindle *a*, which can be screwed towards or away from the mouth of the nozzle.

The water chamber CC is so arranged that it completely surrounds the steam nozzle. The supply of the water is varied by contracting or expanding the conical aperture

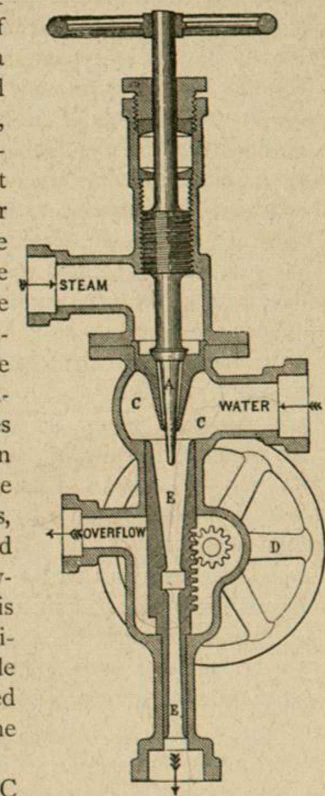

Fig. 185.

below the mouth of the steam nozzle. This is accomplished by moving the conical sliding tube E backwards or forwards by means of the hand-wheel D and the rack and pinion.

If the supply of steam is not properly adjusted to the water, some of the latter will escape at the aperture made in the sliding tube E into the overflow pipe. For instance, if the supply of steam be too small, the current will not have sufficient energy to enter the boiler, and part of it will choke up the sliding tube and escape by the aperture. When this occurs it is only necessary to turn on more steam, or shut off some of the water.

The efficiency of the injector is measured by the temperature of the current of feed water as it enters the boiler, compared to its temperature before it enters the injector. The less the rise in temperature, the more the energy of the steam is utilised. Theoretically speaking, if we measure the units of heat in the feed water as it enters the boiler over and above the heat before it enters the injector, and subtract the amount from the total heat of the steam used, the result ought to give the useful work which the injector does. A great deal of power is wasted in these instruments, as at present constructed, by the formation of eddies. When used for feeding boilers, all the heat represented by the rise of the temperature of the feed water is of course restored to the boiler. As might be expected, the efficiency of an injector increases as the original temperature of the feed water diminishes. These instruments are also used for other purposes besides the feeding of boilers. They have even been employed on a large scale to drain a mine. In this case the work done was represented by about 80 gallons per minute raised through a vertical height of 240 feet. This probably is the greatest amount of work which has ever been accomplished with an injector, and could of course only be undertaken where expenditure of fuel was no consideration.

Water Gauges.—These are used to ascertain the level

of the water in the boiler. The simplest sort consist of three cocks screwed into the face of the boiler at different levels, one being usually at the normal level of the water, one above this in the steam space, and a third lower down at a level below which it is dangerous to allow the water to sink. By opening these cocks in succession the position of the water level can be approximately ascertained.

Another variety in common use consists of a straight glass tube, so fixed that its upper end communicates with the steam, and the lower end with the water space. Cocks are provided for cutting off the connection at either end, and for allowing steam or water to be blown through the glass tube. The latter is fixed at the ends in metal sockets which allow of its being removed and replaced when broken. With this form of gauge the water level is always visible. It is usual to provide a boiler with both forms of gauge, in order that if one gets out of order the other may be available.

Feed-water Heaters.—It is very desirable, whenever it is possible, to feed the boiler with water of the temperature of or about 212°. There are three good reasons for this practice. In the first place, the introduction of cold water into the hot boiler tends to produce the strains due to unequal temperature which have been already commented on. In the next place, it has been observed that water which has been previously heated, otherwise than by surface condensers, exercises a far less corrosive effect on the boiler than cold water, the corrosive action taking place in the heater instead, where its injurious effects are not nearly so important. Lastly, there is of course a very considerable saving of fuel effected by utilising waste heat to raise the temperature of the fuel. Supposing, for instance, the water were raised from 60° to 212°, there would be a saving of 152 units of heat for every pound of water, which is equivalent to about one-seventh of the total heat required to evaporate the water at 212° from the temperature of 60°.

There are three distinct methods in use of heating feed water. In modern marine engines fitted with surface condensers the steam condensed from the engines is used over and over again in the boilers. The temperature of water coming from surface condensers should be about 130°. Unfortunately such water is generally more or less charged with fatty acids, generated by the decomposition of the oils used for lubricating the cylinders, and consequently great care has to be exercised to prevent the rapid corrosion of the boilers. Sometimes, also, the lubricant is carried back into the boiler in the shape of a gelatinous, non-conducting substance, which settles on the crowns of furnaces, and prevents the transmission of heat through the plates. The consequence is, the furnace crowns become over-heated and collapse.

With high-pressure non-condensing engines the exhaust steam is frequently used to raise the temperature of the feed. When the apparatus for utilising the heat of the exhaust steam is properly designed, very excellent results may be obtained with this class of heater, but not unfrequently the steam is *forced* through a series of pipes surrounded with cold water, the result being that the back pressure in the cylinder is unduly raised, and much more heat is thus often lost in the engine than is gained by raising the temperature of the feed.

The third class of feed heater utilises the waste heat from the furnaces before it passes up the chimney, and is admirably adapted to factories where room can be spared. The apparatus usually consists of a series of vertical pipes connected together, through which the feed water is forced. The hot air and gases proceeding from the boiler flues circulate between these pipes, and heat the water contained in them. As, however, the tubes rapidly get covered with non-conducting soot, it is necessary to provide each of them with a scraper driven by machinery, which is constantly travelling up and down the tube as long as the apparatus is at work. A feed heater of this description,

applied to the Lancashire boiler illustrated in fig. 159, has sixty tubes, exposing a total heating surface of 600 square feet. It is situated in the base of the chimney. All heaters of this type are, in reality, low-pressure tubulous boilers, and, as such, should invariably be provided with safety valves.

Chimneys and other Means of producing the Draught.

A chimney promotes a flow of air through a furnace, because the hot air contained in the chimney is lighter than the surrounding atmosphere, which consequently endeavours to force its way into the chimney from below in order to restore the balance of pressure. The only way into the chimney is through the fire-bars and furnace, and in passing through these the air maintains the combustion, and at the same time becoming itself heated, makes the action of the chimney continuous.

In estimating the action of a chimney of a given size in producing a draught, the density, temperature, and volume of the products of combustion must be considered.

The nitrogen which passes through undergoes no chemical change, and consequently its density and volume are unaltered except by the change of temperature. The oxygen combines partly with the carbon and partly with the hydrogen contained in the fuel, while a great portion goes through unchanged like the nitrogen. The portion which combines with the carbon so as to form carbonic acid undergoes no change of volume except so far as it is affected by temperature, for the volume of the carbonic acid gas is the same as that of the oxygen from which it is formed, but its density is of course increased by the weight of carbon taken up. The portion of the oxygen which combines with the hydrogen forms steam, the volume of which is greater than that of the oxygen, but the proportion of utilisable hydrogen in fuel is so small that it is usually left out of account.

Consequently the mixed air and products of combustion which escape from a furnace may be considered as approximately of the same volume as the air which is supplied to the furnace when at the same temperature. One pound of air at 32° has a volume of $12\frac{1}{2}$ cubic feet; and as we have seen that when the blast is produced by a chimney 24 lbs. of air are necessary to consume a pound of coal, the volume of furnace gases for every pound of fuel consumed will be, when reduced to $32^\circ = 12\frac{1}{2} \times 24 = 300$ cubic feet. At any other temperature the volume will equal the volume at 32° multiplied by the ratio of the absolute temperature of the new temperature to the absolute temperature of 32° Thus, taking 2000° as the temperature of the furnace, the volume in the above case

$$=300 \times \frac{2000^\circ + 461^\circ}{32^\circ + 461} = 1497 \text{ cubic feet};$$

and, generally, $V = V_{32} \times \frac{\tau}{\tau_{32}}$, where V_{32} is the volume at 32°, and τ and τ_{32} the absolute temperatures of the gas when at the heat of the furnace and at 32°.

The density of the current depends on the quantity of air supplied per pound of fuel, and on the final temperature of the products of combustion. Thus, if 24 lbs. of air be supplied per pound of fuel, the volume of this quantity of air at $32^\circ = 24 \times 12\frac{1}{2} = 300$ cubic feet. The weight of the mixture of air and fuel is $24 + 1 = 25$ lbs. and the volume at the temperature τ of the furnace gas is $= 300 \times \frac{\tau}{\tau_{32}}$.

The density, or weight of a cub. ft. $= \dfrac{25}{300 \times \frac{\tau}{\tau_{32}}} = \cdot 083 \times \frac{\tau_{32}}{\tau}$.

In the general case let w lbs. be the weight of fuel burned; V_{32} the volume of air supplied at 32°.

Then the total volume of the products of combustion $=$

$w \, V_{32} \frac{\tau}{\tau_{32}}$,

the weight of the products $= \frac{w V_{32}}{12\frac{1}{2}} + w$ lbs.;

the density or weight per cubic foot equals the total weight in lbs. divided by the total volume

$$= \frac{w\, V_{32} + 12\frac{1}{2} w}{12\frac{1}{2} w\, V_{32}} \times \frac{\tau_{32}}{\tau} = \left(\frac{1}{12\frac{1}{2}} + \frac{1}{V_{32}}\right)\frac{\tau_{32}}{\tau}.$$

The quantity $\frac{1}{V_{32}}$ varies in value according to the air supply.

The Effect of Height in a Chimney.—The difference between the weight of a column of outside air of the height of the chimney above the fire-bars, and standing on a base equal in area to the cross section of the chimney, and that of the column of hot air within the chimney is the measure of the force which produces the draught. Let τ_1 be the outside temperature (absolute measure), and H be the height of the chimney in feet.

Then, since one cubic foot of air at 32°, or τ_{32}, weighs $\frac{1}{12\frac{1}{2}}$ $= \cdot 08$ lb., therefore $H\left(\cdot 08 \frac{\tau_{32}}{\tau_1}\right) =$ weight of column of outside air of height of chimney standing on an area of one square foot. The corresponding column within the chimney weighs $H\left(\cdot 08 + \frac{1}{V_{32}}\right)\frac{\tau_{32}}{\tau}$, and the difference between these two weights is the pressure in lbs. per square foot of chimney section which produces the draught. A column of the hot gas equal in weight to this difference is called the head of the chimney; and just as in hydraulics the velocity of discharge of water from the bottom of a full vertical pipe is proportional to the square root of the height of the pipe, so, in the case of a chimney, the velocity with which air would flow, if unimpeded, into the bottom of the chimney is also proportional to the square root of the height of the head. The height of the head, reckoned in feet of hot gas, is found by dividing the weight of a column of external air as high as the chimney, as found above, by the weight of one cubic foot of the hot gas (this gives the height of a column of the hot gas weighing as much as the column of the external air). If we subtract from this the height of the chimney, the difference is the height of the head.

In actual chimneys the velocity of the discharge of the gas is greatly diminished by the resistance opposed by the fire-grate and layer of fuel to the entrance of the air, and also by the friction of the sides of flues, tubes, &c., and of the internal surface of the chimney itself.

Peclet gives the following formula for the height of head necessary to produce a given velocity of the gas in the chimney :—

Let l = the length of the chimney + that of the flue leading to it.

v = area of section of chimney divided by its circumference.

f = co-efficient of friction of sides of flues and chimney, which depends for value on the condition of the surfaces.

G = co-efficient of resistance of grate and layer of fuel to entrance of air.

u = velocity of gases in chimney.

g = acceleration due to gravity ; and

h = height of head in feet.

Then, according to Peclet,[1] $h = \frac{u^2}{2g}\left(1 + G + \frac{fl}{v}\right)$.

The value of the co-efficients varies according to circumstances. When the surfaces of the flues are sooty, $f = \cdot 012$. With ordinary grates, burning from 20 to 24 lbs. of fuel per square foot of grate surface per hour, G = 12, and the formula then becomes—

$$h = \frac{u^2}{2g}\left(13 + \frac{\cdot 012 l}{v}\right).$$

[1] See Rankine's *Manual of the Steam Engine*, p. 287. Ninth edition.

If the head is given, then the velocity of the gas can be calculated from the same formula; and when this is ascertained, the weight of fuel which can be consumed in a given time may be calculated on the supposition that each pound of coal requires 24 lbs. of air = 316 cubic feet at the ordinary temperature (60°) of the atmosphere.

The use of very high chimneys is in many situations a necessity, not in order to create the draught, but in order to discharge the noxious products of combustion at a considerable distance above animal and vegetable life ; otherwise a forced blast might often be more advantageously employed. It is considered that a chimney is most efficacious in producing a draught when the temperature inside it is about 600°, and at this temperature about one-fourth of the available heat of combustion is wasted in creating the draught.

When a forced blast is produced by means of a fan, blast-pipe, or air injector, the products of combustion may be cooled down as far as is found practicable and convenient; and as much less air is required to effect combustion, the saving of heat may be very considerable. On the other hand, heat must be expended in order to produce a forced draught. Thus in the case of the blast-pipe the heat expended is represented by the excess of back pressure in the cylinder.[1] In the case of a fan, the heat consumed in driving the fan must be taken into account ; and when an

[1] According to Mr. D. K. Clark's experiments the excess of back pressure over and above the pressure of the atmosphere, caused by the use of the blast-pipe, varies approximately (1) as the square of the speed of piston ; (2) as the pressure of the steam at the commencement of the exhaust ; (3) inversely as the square of the area of the nozzle of the blast-pipe. He also found that the back pressure was largely increased by the presence of liquid water in the spray. As to the amount of the back pressure in certain cases the reader can consult the examples of diagrams from locomotive cylinders on page 338. Mr. Clark also states the vacuum in the smoke-box to be about 70 per cent. of the blast pressure, while the vacuum in the fire-box is from one-third to one-fourth of the same pressure, and the rate of evaporation varies about as the square root of the vacuum in the smoke-box.

air injector is used, the heat expended in producing the draught is represented by the total heat of formation of the steam used in the injector.

Forced draught.—A forced draught is now frequently applied to the furnaces of marine boilers, especially in ships of war. In torpedo boats it is necessary to develope immense power out of a comparatively small boiler, and some sort of artificial draught becomes an absolute necessity. A blast-pipe is of course impossible, as the engines are condensing, and would, moreover, be quite inapplicable on account of the noise and shape of the funnel. The method which has been adopted is to force the air into the furnace by means of a rotary fan, driven either from the main machinery, or else by a separate engine. If the blast were directed solely beneath the fire by means of the device of a closed ash-pit, it would always be leaking outwards through the furnace door, and would, whenever the latter were opened for fresh fuel, cause the smoke and flame to fly out in the face of the stokers. To obviate this, the plan has been adopted of closing the stoke-hold so as to make it air-tight, and then forcing the air into the closed chamber, which can only escape through and over the fuel and boiler tubes to the funnel. When the furnace door is opened, the compressed air in the stoke-hold rushes through it to the tubes, thus preventing the escape of flame. In this way most remarkable results have been obtained. The defect of the system is that it is difficult, in a boiler of moderate size, to provide sufficient surface to absorb the heat generated by the large amount of fuel which can be burnt on the grate. The result is that the water evaporated per pound of fuel is necessarily low.

The application of forced draught is by no means limited to the boilers of torpedo boats. In large men-of-war the system is also applied for the purpose of obtaining a large additional supply of steam when extra speed is required. The general result attained may be stated as follows. With

natural draught about $10\frac{1}{4}$ horse-power are indicated per square foot of fire-grate at full power; while with forced draught between 16 and 17 horse-power are obtained. The pressure of air being about two inches.

In the mercantile marine forced draught is beginning to receive considerable attention, for two reasons. First, its application will enable a considerable saving to be effected in the weight of boilers, provided always that the evaporation per pound of coal burnt be not seriously diminished. Second, it enables very inferior and cheap fuel to be utilised.

In the mercantile marine, hitherto, the closed ash-pit has been used instead of the closed stoke-hold. Fig. 186 illustrates the system applied by Mr. Howden successfully

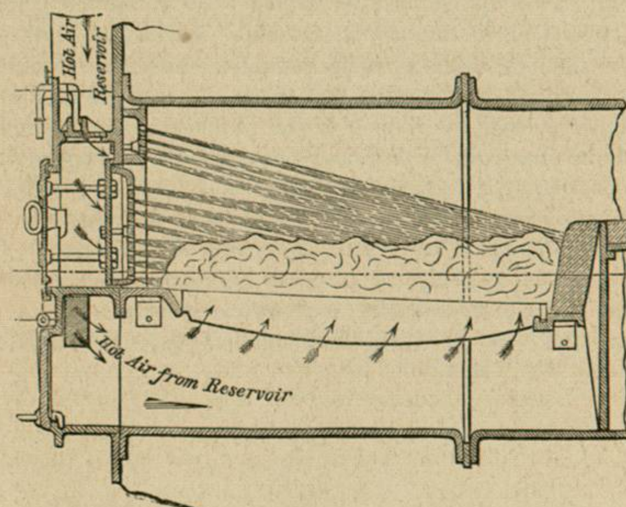

Fig. 186.

to the boiler of a merchant steamer. The ash-pit is closed in front by a door, and the furnace door is double with a hollow chamber between its outer and inner faces. Air under pressure is supplied beneath the fuel through the ash-pit, and above the fuel through the holes in the inner furnace door, the air issuing through these holes being under considerably higher pressure than that in the ash-pit. The object of this double admission is to secure the complete combustion of the fuel with a very moderate supply of air, and thus to increase the temperature of the products of combustion. The air supply is heated by the waste gases from 180° to 200° above its ordinary temperature, and whenever the furnace door is opened the current of air is cut off for the moment so as to prevent the sudden cooling down of the furnace.

At first sight it would appear that the forced draught system is of no special advantage where economy of fuel is a primary consideration; for, although by its use the grate area may be diminished, nevertheless, the heating surface and the total weight of boiler cannot be reduced. It must however be borne in mind that if the supply of air be properly regulated, the volume of the products of combustion will be greatly diminished, and their temperature increased; consequently, a less heating surface is required to produce the same evaporative results per pound of fuel than when natural draught is employed. Also with forced draught it is possible to make use of tubes of comparatively small diameter, and consequently a considerably increased heating surface can be obtained without increasing the dimensions of the boiler.

CHAPTER X.

CONDENSATION AND CONDENSERS.

The object and advantages of condensing steam—General description of condensers—Quantity of water required to condense steam—Objects of surface condensation for marine engines—Description of a jet condenser for a stationary engine—Description of a marine surface condenser—Air-pumps—Ejector condensers—Method of indicating the vacuum.

THE condenser may, in a certain sense, be described as having the inverse functions of the boiler; for, whereas the latter is employed to raise the medium with which the engine works to the superior limit of temperature, the purpose of the latter is to reduce the inferior limit of temperature as far as possible. The boiler fulfils its purpose by converting the feed water into steam, and the condenser by re-converting that steam after it has done its work into water.

The advantages from the thermal point of view of condensing the steam, instead of allowing it to escape into the open air at a little above the atmospheric pressure, are very easily explained by reference to the principles which enable us to calculate the maximum efficiency of heat engines (see p. 88). Suppose, for instance, that we have two precisely similar engines working with steam of 50 lbs. pressure per square inch absolute, and one provided with a condenser, while the other discharges the exhaust into the open air. Suppose, also, that the former expands down to a pressure of 3 lbs. absolute, and the latter down to a pressure of about 3 lbs. above the atmosphere, say 18 lbs. absolute.