SUPERHEATERS AND SUPERHEATED STEAM.

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Nature of Steam Superheating.

Superheated steam is steam heated above the temperature of saturated steam at corresponding pressures; that is, steam at a temperature higher than that at which it evaporates at that pressure.

Even dry saturated steam cannot be obtained except with a slow fire and large boiler capacity, as spray is carried with the steam if the steam rises from the water at a velocity greater than about 2 ft. 6 in. per second.

Superheating, as carried out in ordinary practice, increases the temperature and volume at constant pressure. The value of superheating depends mainly on the fact that the volume of the steam, and consequently the work done, is increased, while the heat expended is increased to a proportionately small extent. Another method of obtaining the same result is to allow the steam to expand at constant pressure without doing work.

Steam cannot be superheated in the presence of water, as the water takes up the heat for further evaporation. Fairbairn, Tait, Hirn and Siemens all found that saturated steam was not a true gas, and that on the application of heat the expansion at first was greater than it should be. Siemens found that steam apart from water increases rapidly in volume from 212° to 230°F. and then behaves as a permanent gas.

The superheat falls off rapidly from radiation, about 30 per cent. being lost between engine and boiler even with a short steam pipe, the reason being that saturated steam owes its heat-retaining properties to the spray carried in it.

Aim in Superheating.

In addition to increase of work due to increase of volume of steam mentioned above, the greatest advantage is gained in the engine cylinder, and is due to the immediate absorption of the film of water on the metal surfaces by the surplus heat, thereby counterbalancing cylinder condensation which is the heaviest loss in the expansive working of steam.

In this connection superheating has an advantage over steam jackets, as the heat is applied exactly when and where it is wanted—up to cut-off and inside the cylinder—while a steam jacket wastes some of its heat in warming the exhaust, and applies the heat outside the cylinder.

Early Attempts at Superheating.

The economy of steam superheating was discovered by Richard Trevethick in 1828, when reporting on the engines at Binner Downs, in Cornwall. The engineer of the mine built in the cylinders with brickwork, with a fire-grate underneath and flues round the cylinders. For a 70 in. cylinder, five bushels of coal used under the cylinder reduced the coal necessary for the boiler from 108 bushels to 67 bushels, a saving of one third of the coal. The pressure in this case was 45 lbs. above atmospheric, and the number of strokes per minute was eight. The injection water used with the cylinder fires was 13 gallons per stroke, with a temperature range from 70° to 104° F. while without the cylinder fires it was 15½ gallons from 70° to 112°.

In 1832, Trevethick invented a tubular boiler with a superheater between the boiler and cylinder, the cylinder being also jacketed with the waste gases.

In 1802, Trevethick had made an engine with the cylinder inside the boiler, in order to do away with cylinder condensation.

Owing to the difficulty in regulating the amount of superheat, the use of superheated steam was dropped until about 1850, when it came to the front again, many forms of superheater being brought forward, both in the boiler flues and separately fired. The difficulty of keeping the valves steam-tight and providing efficient lubrication was overcome by using asbestos packings and brass bushes with plumbago plugs.

More Recent Attempts.

In 1859, Penn fitted up a superheating apparatus on the P. & O. S.S. *Valetta*, of 216 I.H.P., which affected a saving of 20 per cent. of the coal previously used. The apparatus consisted of two horizontal faggots, each of 44 tubes 2 in. diameter, in the smoke-stack. The tubes were in three wrought-iron boxes, welded at the corners and closed with flanged joints. The steam passed to the centre box, thence through the tubes to the end boxes and thence to the engine. The boiler surface was 19 sq. ft. per H.P., and the superheating surface 2¾ sq. ft. per H.P. The pressure in the boilers was 20 lbs. above atmospheric and the superheat 100° F.

In 1860 Parson and Pilgrim fixed a superheater on to H.M. steam tug "*Bustler*," with a resulting economy of 25 per cent. in fuel. The superheater consisted of two horseshoe pipes over the fire grate in the internal flue. The pressure was 8½ lbs. above atmospheric, and the superheat 144° F. With the same apparatus on Cornish and Lancashire boilers, a saving of from 30 per cent. to 40 per cent. was obtained.

In the same year Partridge fitted superheaters to H.M.S. "*Dee*," with the result that there was a saving of 20 per cent. to 25 per cent. in fuel. This superheater was a cylinder fitted with tubes and placed in the uptake, the hot gases passing through the tubes and the steam round them. This was worked at a temperature of 360° to 390° F. In 1860 the total work done by engines using Partridge's superheater aggregated 5,000 H.P.

In a paper written in 1860, J. Wethered advocated mixed steam—*i.e.*, a mixture of saturated and superheated steam—saying that the common forms of superheater then in use necessitated an increase in expenditure for repairs to parts damaged by the hot steam which would quite balance any economy in coal.

Reasons for Former Abandonment.

The principal reason for the abandonment of superheating was the trouble at the valve faces and in the cylinders from the decomposition and destruction of lubricants. The former caused the setting free of fatty acids which attacked the metal, and the latter caused the cutting of the metal owing to the parts working dry.

There is now very little likelihood of this trouble recurring, as with good hydrocarbon oils it is possible to work at temperatures as high as 2,000° F. (*e.g.*, in gas engines). The principal trouble nowadays is the design of a suitable admission valve, a piston valve being probably the best. Much of the trouble of cut valves is due, not to superheating, but to working with steam alternately wet and superheated, owing to poor supervision. This causes oil to become hard in the cylinders, and often necessitates reboring. Some superheaters again are faulty in construction, having a by-pass for the steam but not for the furnace gases; this causes deterioration when the steam is shut off from the superheater.

Re-introduction of Superheating Apparatus.

The principal cause leading to the re-introduction of superheaters was the increased efficiency of engines and boilers and the consequent competition. Nearly all modern superheaters are old forms revived with modification.

Forms of Superheater, Trevethick.

In Trevethick's superheater mentioned above there are twelve tubes in the boiler connected top and bottom in boxes. These are arranged in a ring with the superheater tubes in the interior of the ring. The fire for the superheater is in the lower part of the ring. The steam passes from the top box to the superheaters, which consists of six tubes, and from their to the engine, which is jacketed with the furnace gases.

Gehre.

As applied to a Lancashire boiler Gehre's superheater consists of two sets of tubes fixed in the upper flue. The steam passes from the anti-priming pipe along one set of tubes, across to the other and back to the front of the boiler, passing thence to the engine.

Hick-Hargreaves.

The Hick-Hargreaves superheater consists of a nest of U tubes bent to a large radius at the bottom, fixed at the end of a Lancashire boiler, in a plate which forms the bottom of a box. This box is divided by a vertical diaphragm separating the downward end of the tubes from the upward. Only a portion of the steam is superheated, regulation being effected by means of a by-pass valve. There are also main valves by which the steam can be shut off from the superheater and the gases from the flue diverted so that the superheater may be taken out without interrupting the working of the boiler.

MacPhail and Simpson, Figs. 1, 2, 3, 4.

The MacPhail and Simpson superheater differs somewhat from the preceeding forms, it being arranged in such a way that part of the superheat is used to evaporate more water. The superheater is in two parts—the superheater proper, and the steam generator of radiating tubes. As applied to a Lancashire boiler, there are two nests of vertical steel tubes, expanded top and bottom into cast steel boxes or headers, placed in the downtake. The steam passes from the anti-priming pipe to the first top box, through the tubes to the first bottom box, thence to a block passing into the bottom of the boiler and through a copper pipe along the bottom of the boiler under the internal flues to the front, returning to the second bottom box, thence through the tubes to the second top box, then into the boiler, along a copper pipe over the flues but below the water-line, to the main steam stop-valve. The steam is thus superheated, part of the heat radiated to the water further superheated, more heat radiated to the water and then sent to the engine at a temperature higher than the boiler temperature.

The amount of superheat depends on the proportion of heating surface to radiating surface. The radiating pipes give off the extra superheat which would be dangerous with a heavy fire, and prevent the superheater becoming a condenser when the fires are green and the temperature of the flue gases low. This tends to keep the amount of superheat of the steam leaving the boiler very constant, even with great variation in the rate of evaporation.

With a Babcock & Wilcox boiler there is room for only one set of tubes between the drum and the water tubes, and one pipe in the drum, below the water-line. In this case the steam goes from the anti-priming pipe to the upper box of the superheater, through the tubes to the lower box, thence into the drum and through the pipes to the stop-valve. There is no incrustation in the superheating tubes, as all the water and any scum which comes over is caught in the top box from which it can be drained off.

Schwoerer.

Schwoerer's superheater is an attempt to reduce the space occupied, by employing a coil of pipes with gills on them both inside and outside, thereby increasing the heating surface without increasing the bulk.

Sinclair.

In Sinclair's superheater the tubes, instead of being expanded into plates, are flanged and bolted to the cross inlet and outlet pipes. The gases from the smoke-box are led to the back of the boiler through the superheating tubes and down the sides to the centre flue.

Fehrman.

In Fehrman's superheater each element consists of two concentric wrought-iron tubes with the steam circulating between them and the furnace gases inside and outside. In the annular space are corrugated copper plates, which increase the heating surface, but are not called upon to stand any strain.

A marine form is shown in Figs. 6 and 7. It consists of a box of tubes in the uptake through which the steam passes, the hot gases passing round the tubes. Dampers are fitted in the uptakes which may be placed in the position A or B to compel the gases to pass through the superheater tubes or to go direct to the funnel, and the superheater valves are so arranged that the steam may be made to pass direct to the engines or through the tubes. In ordinary working all valves would be kept partially open and mixed steam used, the temperature being regulated by the suitable adjustment of the valves.

Schmidt.—Fig. 5.

The Schmidt superheater consists of a coil of tubes through which the steam passes and round which the flue gases pass. The coils are divided into two series, the bottom two coils being called the fore-superheater (A), and the remainder the main-superheater (C). The coils are arranged watch-spring-like and placed one above the other.

The steam leaves, the boiler by a perforated tube in the steam space, enters the lowest coil and passes from that to the one above it. It then enters the upright chamber B (called the after-evaporator), and from there passes direct to the topmost coil of the main superheater. It then flows downwards through the successive coils in a direction opposite to that of the flow of the chimney gases, and leaves the superheater at its maximum temperature from the lowest coil of the main superheater, and goes thence to the engine. The advantages claimed for this superheater are :—(*a*) The tubes nearest the furnace gases have wet steam flowing through them at a high velocity, and so are not subject to injury ; (*b*) The steam in the main superheater is moving towards a hotter region during the whole of its passage, thus securing a high degree of superheat. The superheat is regulated by a valve at the top of the vertical flue which lets any desired amount of the flue gases go direct to the chimney without passing through the superheater.

The tubes are not part of the evaporating surface, but merely another method of using part of the heat generated as well as using some of the waste heat which would otherwise escape in the furnace gases. The Schmidt superheater, however, is as a rule separately fired. A full description of this superheater, with tests, will be found in Proc. Inst. C.E., 1896, vol. cxxviii., p. 60.

Babcock and Wilcox.

The Babcock and Wilcox superheater consists of solid drawn steel tubes bent to a U shape and connected at both ends to boxes, one of which receives saturated steam from the boiler, while the other supplies superheated steam to the stop-valve. This may be placed between the water-tubes and the shell, in which case a flooding arrangement is provided by means of which the superheater can be filled with water from the lower part of the drum. When this is done the superheater becomes part of the boiler heating surface.

The B. & W. separately fired superheater is composed of a series of boxes or manifolds connected together by U-shaped tubes. The steam enters the lowest box and is conveyed through the tubes to the second, third, and fourth boxes, and so on, passing from the last box back to the steam main. The furnace gases pass through a perforated wall which muffles the flames, into the superheater chamber and thence through a similar wall to the chimney. Very little fuel is required, the amount necessary for 60° of superheat being roughly about one pound of coal to 220 lbs. of steam, or two tons of coal for every million pounds of steam. These types of superheater can be applied to Cornish, Lancashire, or other shell boilers with slight modifications.

For further descriptions of different types of superheaters, see *The Engineer*, 21st February, 1896, p. 196.

Results of Tests.—Gehre.

Superheater behind the boiler, separately fired.

Boiler surface	831 sq. ft.
Superheating surface	646 ,,
Economy in steam due to superheat ...	5 per cent.
,, ,, coal ,, ,, ...	34 ,,
Superheat	40° F.
Gauge pressure	110 lbs.

Hick-Hargreaves, 1895.

Corliss engine, tandem compound, cylinders 18 in. and 36 in., stroke 4 ft., I.H.P. 300.

Boiler surface	1,195 sq. ft.
Superheating surface	120 ,,
Economy in steam	19 per cent.
,, ,, coal	9·6 ,,
Superheat	45·2° F.

Macphail and Simpson, 1894.

Corliss engine, simple, condensing, cylinders 28 in. x 4 ft. 6 in. stroke, I.H.P. 328. Test by Isaac Holden, Rhiems. Lancashire boiler.

Boiler surface	2,287 sq. ft.
Economy in steam	6·8 per cent.
„ „ coal	36·2 „
Superheat, ...	56·5° F.

Boiler pressure, 73 lbs. without superheat, 91 lbs. with.

1895.

Test by H. Bruce & Sons, Kinleith.
Five Lancashire boilers.

Boiler surface	930 sq. ft.
Economy in steam	8 per cent.
„ „ coal	32 „
Superheat	93·2° F.

Boiler pressure, 73 lbs. without superheat, 82 lbs. with.

1895.

Test by Thornliebank, Glasgow.
Lancashire boiler.

Boiler surface	955 sq. ft.
Gain in water evaporated per lb. of coal ...	18·2 per cent.
Superheat	16° F.
Boiler pressure	72 lbs.

1893.

Test by Patchell.
Babcock & Wilcox boiler. I.H.P. = 130.

Boiler surface	1,827 sq. ft.
Economy in steam	5·7 per cent.
„ „ coal	13·1 „
Superheat	16° F.
Boiler pressure	135 lbs.

Schwoerer.

Test by Meunier.

Superheat	100°—118° F.
Economy in steam	20 —25 per cent.
„ „ coal	14 —20 „

Test by Unwin.

Superheat	118°—126° F.
Economy in steam	13 —21 per cent.
„ „ coal	18 —20 „

Test by Meunier & Ludwig.

Three boilers used with a total heating surface of 4,842 sq. ft. Corliss engine, triple expansion, cylinders 22 in., 31½ in., 45 in. Stroke, 4 ft. 6 in.

I.H.P. 809 from two boilers with superheater, 805 from three boilers without superheater.

Superheat	... 180° F.
Economy in coal	... 18·4 per cent.
„ „ steam	... 14·7 „
Loss in steam pipe without superheat	... 5·4° F.
„ „ „ „ with „	... 23·4° F.
„ „ jackets „ „	... 38° F.
Superheat at the cylinder ...	... 119° F.
Oil used with saturated steam in 11 hrs.	... 8·8 lbs.
„ „ „ superheated „ „ „ „	... 11·7 lbs. of a more expensive oil.

Uhler.

Test by Meunier & Ludwig.

The same boilers and engine were used as above, but with a Uhler superheater.

Superheat	... 111·6° F.
I.H.P. with superheated steam ...	... 801
„ „ saturated „ ...	... 788
Economy in coal	... 5 per cent.
„ „ steam	... 14 „
Loss of superheat in steam pipe ...	... 39·6° F.
Superheat at cylinders	... 72·0° F.

The superheater was separately fired, the coal used being 11 per cent. of the whole.

For tests of Schmidt superheater, see Proc. Inst. C.E., 1896, vol. cxxviii., p. 90, the curves being given in Figs. 11-15.

Superheaters for Locomotives.

During the past year the Prussian Railway authorities carried out experiments on the effect of superheating by fitting one of each of two pairs of locomotives with Pielock superheaters built round the tubes immediately under the dome. The engines were run on the same journeys alternately, under the same conditions as far as possible. It was assumed that similar engines hauling equal weights of trains at the same speed and under similar conditions exerted the same power. The economy was estimated from a knowledge of the amount of water evaporated, and the temperature and pressure of the steam.

With 116° F. of superheat the experiments showed a saving of 16 per cent. of water and 12·3 per cent. in coal, at a pressure of 185 lbs. per sq. in. With 18° superheat the saving is calculated to be 2½ per cent. in water and 2 per cent. in coal; and with 72° superheat, 10 per cent. in water and 7 per cent. in coal.

(P. Inst. C.E., 1904, vol. clvii., p. 400).

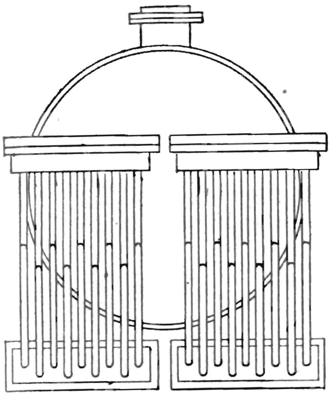

Fig 1

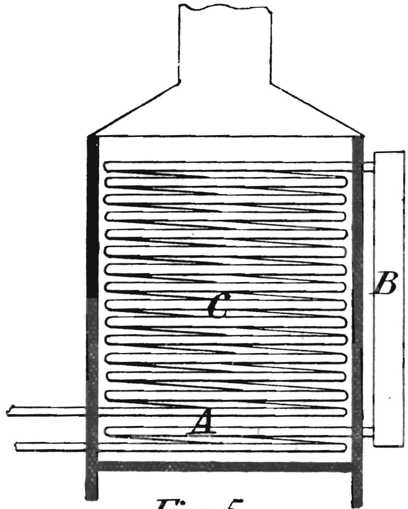

Fig 5

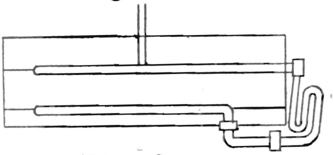

Fig 2

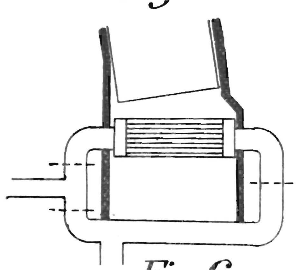

Fig 6

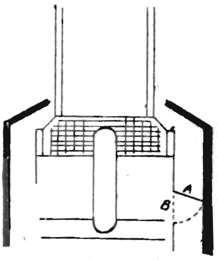

Fig 7

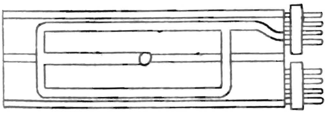

Fig 3

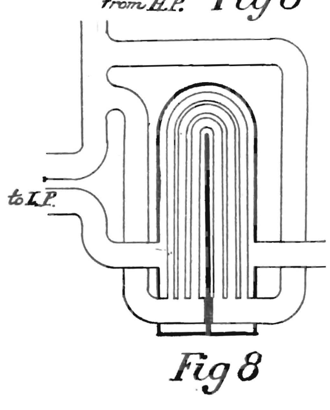

Fig 8

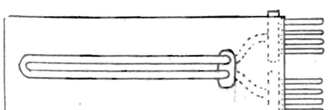

Fig 4

Superheaters on Compound Engines.

The superheaters mentioned and described above are all for simple engines or for the first cylinder of compound or triple expansion engines, but superheaters may also be used with advantage between the cylinders of compound engines. The steam leaving the first cylinder will probably have at least 30 per cent. of moisture when it reaches the second cylinder, no matter to what degree it was superheated. This will cause a loss of work in the second cylinder, and a consequent disproportionate amount of work will be done by the first cylinder.

If we suppose that the steam leaving the first cylinder has the same quality as the steam supplied by the boiler, and if we wish to give it the same amount of superheat, we shall have to transmit to it the same amount of heat (approximately). As, however, this steam is less dense, the capacity of the second superheater will have to be greater.

A superheater designed by Schmidt for use between the cylinders of a compound engine is shown diagramatically in Fig. 8.

Turbines.

As there is no cylinder condensation in turbines, the effect of superheating should be merely the gain in efficiency which we should expect from thermodynamical considerations. This is about 0·1 per cent. economy in steam consumption for every 3° F. of superheat. The actual gain however is about 1 per cent. for each 3° F. together with a doubling of the capacity of the turbine for about 37° superheat. This increase is probably due to the reduction in fluid friction which is effected by using superheated steam.

Some tests of a Parsons turbine coupled to a 500 k.w alternator at Blackpool, gave the following results:—

Pressure above Atmospheric at Stop-valve.	Superheat, Degrees F.	Load, k.w.	Steam Used.	
			lbs. per hour.	lbs. per k.w. hour.
150	0	502	11,600	23·1
135	0	497	11,953	24·0
146	70	515	11.000	21·35
133	66	507	10,693	21·1

SPECIFIC HEAT OF SUPERHEATED STEAM.

Thermo-dynamics.

The specific heat of superheated steam is not a constant, but depends on the temperature and possibly also on the pressure. This makes it difficult to draw an entropy-temperature diagram for superheated steam. The usual value taken is 0·48, which will be found fairly correct for temperatures between 125° and 225° C. (257° and 437° F.). A more exact value however is given by :—

$$K = 0{\cdot}305 + 5{\cdot}75 \times 10^{-6} t^2,$$

where t is the temperature centigrade.

The theoretical effect of superheating may be studied most easily on the entropy-temperature diagram. To draw the entropy-temperature curve for superheated steam, we must assume a value for the specific heat at constant pressure: if we assume the value 0·48 we get:—

$$\phi_2 = \int_0^{T_2} \frac{dQ}{T}$$

$$\phi_1 = \int_0^{T_1} \frac{dQ}{T}$$

$$\phi_2 - \phi_1 = \int_{T_1}^{T_2} \frac{dQ}{T}$$

Now $dQ = K\,dT$

$$\text{Therefore } \phi_2 - \phi_1 = \int_{T_1}^{T_2} \frac{K\,dT}{T}$$

$$= K \left[\log_e T\right]_{T_1}^{T_2}$$

Now suppose that we are heating the steam from 382° to 540° F.

$$T_1 = 842° \text{ F. abs.}$$

$$T_2 = 1{,}000° \text{ F. abs.}$$

$$= 0{\cdot}48 \,(\log_e 1{,}000 - \log_e 842)$$

$$= 0{\cdot}48 \times 0{\cdot}172$$

$$= 0{\cdot}08256$$

This is the difference of entropy between the steam at 382° F. and the steam at 540° F.

Case I.—No Superheat.

Let us suppose that the feed-water is received into the boiler at 85° and heated to 382° F. The entropy-temperature curve is AB, Fig. 9. Suppose the water is converted into steam at 382° which corresponds to a pressure of 200 lbs. This absorption of heat is represented by BC. Let the steam now expand adiabatically till the pressure falls to 0·6 lbs. abs. which is the pressure corresponding to 85° F.; this expansion is represented by CD. Some of the steam will condense during expansion, and if CE be the line of dry saturated steam, the quality at any point is the ratio between the horizontal distance between AB and CD to that between AB and CE. Now let heat be extracted from the steam, at constant temperature, till the whole of it is condensed; this is represented by DA. The heat supplied is *a*ABC*d*, the heat converted into work is ABCD and the efficiency is

$$\frac{ABCD}{aABCd} = 0{\cdot}31.$$

Case II.—With Superheat.

Suppose the steam to be superheated before expansion takes place, from 382° to 540° F. and that the expansion is then adiabatic. CG in Fig. 10 is the curve for the superheating. It will be seen that the line GK of adiabatic expansion cuts the line CE of dry saturated steam at H. This shows that the steam is superheated from G to H, saturated at H, and wet from H to K. The heat supplied is *a*ABCG*g*, the heat converted into work is ABCGK and the efficiency is

$$\frac{ABCGK}{aABCGg} = 0{\cdot}32.$$

The superheat supplied is *d*CG*g* of which DCGK is converted into work. The efficiency of the superheating action is

$$\frac{DCGK}{dCGg} = 0{\cdot}41$$

In practice, the expansion with saturated steam begins at a point earlier than C, causing a loss of efficiency. The actual diagram, of course, has not a straight line such as CD representing the expansion, the true shape of the diagrams indicating a much greater gain in efficiency in actual practice from the use of superheated steam.

Conclusions.

To obtain the full advantage of superheating, the temperature should be raised sufficiently high to secure dry steam throughout admission and up to release, for which purpose the steam should be supplied to the engine at a temperature of about 650° F. For the same horse-power this amount of superheat will reduce the steam consumption by about one half.

The greater the amount of superheat the less will be the interchange of heat between the working fluid and the cylinder walls, while with very great superheat the cylinder walls act almost as though they were non-conducting.

The practical difficulties in using superheated steam have been overcome, the tubes showing no scaling or burning, even after long periods of continuous work. There is no trouble in lubricating if the oil is of good quality and is supplied with regularity.

The best results will be obtained with a late cut-off, as any cause tending to produce cylinder condensation when using saturated steam, will tend to neutralise the useful effects of superheated steam in the cylinder.

The steam parts with its superheat immediately upon admission to the cylinder, and unless the superheat is about 200° F. it will part with all its superheat and leave merely saturated or wet steam in the cylinder.

In designing an engine to work with superheated steam, the chief point to be considered is the design of the admission valve. This valve, being subjected to the maximum temperature of the steam, should be practically frictionless, to avoid trouble in lubricating it. For small powers a piston valve without spring rings, accurately ground to fit a cast iron bush, may be used, while for larger powers several types of equilibrium valve have been tried successfully. Except for low pressures and moderate superheat, the ordinary slide valve is not suitable.

Explanation of Figures.

ERRATUM.

Fig. 9, bottom—·546 should be 1·546.

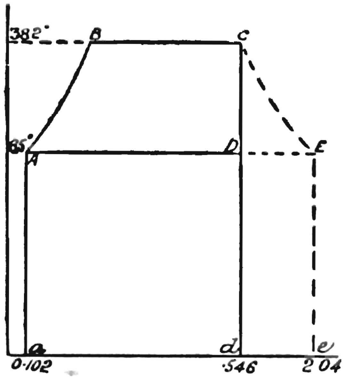

Fig 9

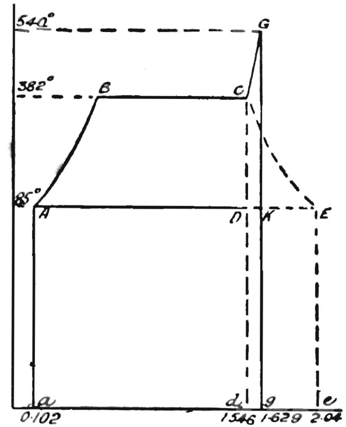

Fig 10

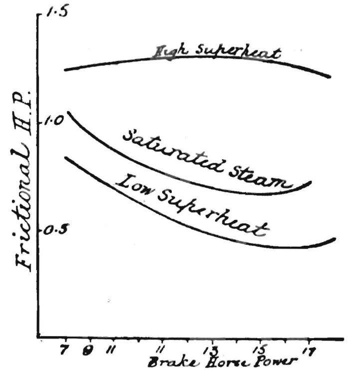

Fig 11

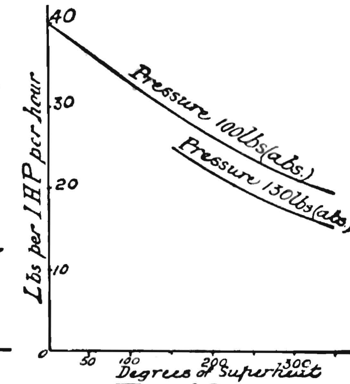

Fig 12

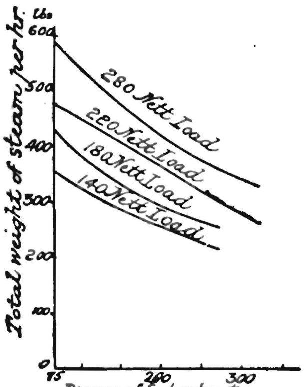

Fig 13

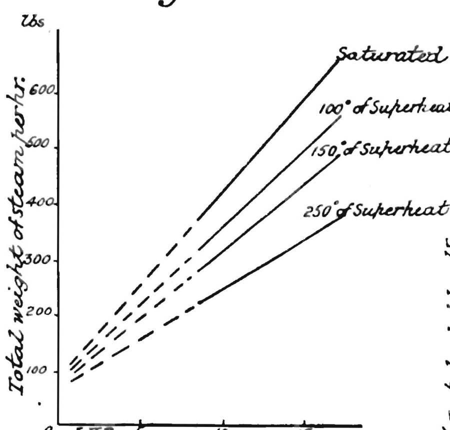

Fig 14

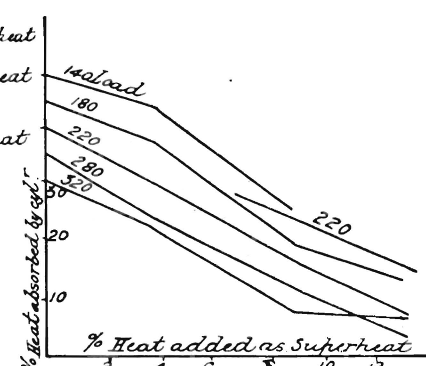

Fig 15