cutting off the steam as early in the stroke as may be necessary for that purpose, but the throttle valve remains wide open until it is released by the lever being brought again into the central position at the end of the run.

Engine Details.—There are such a number of excellent books published on the construction of steam engines, to which the student may refer, that it is needless to write at length on this point. Suffice it to say that, speaking generally, in England piston valves are usually preferred on account of their simplicity, on the Continent double-beat drop valves are most common, while in America the Corliss engine is the favourite, but for reversing engines the piston valve is almost universally employed all over the world. In all three instances the common slide valve is usually fitted on the smaller engines.

For engines running only in one direction a single crank is most common, but for engines intended to reverse and run in either direction, at least two cylinders coupled to cranks set at right angles to each other are requisite, as a single engine is liable to stop with the crank in such a position that the engine cannot be started again without being first barred round off the "dead centre," involving a serious waste of time.

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CHAPTER XXXI.

THE SUPPLY OF POWER—(*Continued*).

(3) Gas Engines.

Natural Gas.—In some parts of the United States, and near the Caspian, gas issues from the ground at pressures occasionally as high as 700 lbs. on the square inch. Analyses of this gas have been given on p. 139, vol. I., of this work. It is an exceedingly rich gas, showing a heating value of 600 to 1,000 B.T.U. per cubic foot, clean and free from sulphur, giving a beautiful clear heat in a furnace, and suitable for use in gas engines. Those interested in the subject of natural gas will find a paper dealing with it, by Mr. Andrew Carnegie, in the *Iron and Steel Institute Journal*, vol. i., 1885, pp. 168-175.

Blast-Furnace Gas.—The blast furnace is a gas producer on a vast scale. For every ton of iron made in it, it discharges from 110,000 to 180,000 cubic feet of combustible gas, the average being about 130,000 cubic feet. The potential heat contained in this gas represents not less than one-half of all the heat obtainable from the coke. This vast supply of potential power and heat was allowed to go absolutely to waste until Budd, of Ystalyfera, in South Wales, in 1845, patented its use for heating stoves and boilers.

Blast-furnace gas has usually a composition by volume lying between the following limits:—

Carbonic oxide,	25 to 32 per cent.
Hydrogen, marsh gas, &c.,	2 to 5 ,,
Carbonic acid,	8 to 12 ,,
Nitrogen,	54 to 60 ,,

Its calorific value is from 85 to 125 B.T.U. per cubic foot—usually about 90 to 110 B.T.U.

As a rule, nearly one-half of the gas is now employed to heat the hot blast stoves, and, where steam blowing engines are employed, the balance is consumed in heating the boilers required to drive them; any surplus remaining after this passes to waste, or is utilised for some small subsidiary purpose.

But when the gas, instead of being used to drive steam engines by means of boilers interposed between the furnace and the engine, is used directly in a gas engine, the same amount of work can be accomplished with the expenditure of much less gas, and a considerable margin is then available for providing power for the steel works.

The volume of gas made is nearly one-third greater than that of the air driven in by the blowing engines. The quantity, therefore, is remarkably regular, as also is the quality, providing the furnaces are working regularly, and storage holders are consequently unnecessary.

Cleaning Blast-Furnace Gas.—The mechanical pressure of the blast drives off with the gas as it leaves the throat of the furnace, numerous particles of coke, ore, lime, &c. The coarse pieces are deposited in a dust catcher provided for that purpose, consisting of a tall cylindrical casing with a conical bottom closed by a door. The casing is two or three times the diameter of the "down-comer," which enters vertically at the top, so that the current of gas, rushing vertically downwards, throws the solid particles to the bottom of the vessel, where they are retained by the action of gravity, while the gas freed from the coarser particles flows slowly upwards. By opening the bottom door at intervals, these are blown out into small trucks or barrows placed there to receive them. The gas then passes through various dry cleaners, which consist of boxes or cylinders containing various arrangements of baffle plates, whereby the direction of flow is suddenly changed, and the finer particles are given a chance to settle under the action of gravity, instead of being driven on by the rush of gas. The smallest and lightest portions are most difficult to get rid of; they travel with the gas through the hot blast stoves, and boiler flues, appearing as a white smoke at the top of the chimney, forming a cloud which may stretch for miles across the landscape.

These fine gritty particles must be removed if the gas is to be used in gas engines, or they will soon wear out the cylinders. To effect this the gas is passed upward through washing towers, meeting on its way fine sprays of water falling from the top, the tower being often filled with trays or gratings to expose a large amount of wetted surfaces. The moisture surrounding the particles of dust increases their weight sufficiently to enable a further portion to settle under the action of gravity, but to remove the last traces the gas is passed through revolving fans, into which jets of water are sprayed. The difference in gravity between the gas and the wet solids contained in it is thus increased artificially by centrifugal force; the heavy water and wet dust is flung outwards against the case of the fan, and the light gas passes on, either direct to the engine, or through a second or third fan, as may be found necessary. The use of a fan also ensures a supply of gas to the engines at a sufficiently steady pressure, even when the furnace bell is lifted or the dust is being blown out of the mains. The Theisen washer is a specialised form of fan, which is largely used for the purpose.

By these means the dust, which may amount to 4 or 5 grammes per cubic metre (·007 to ·009 grain per cubic foot), may be reduced to 0·02 or 0·01 gramme, which is sufficiently clean for use in a gas engine.

Blast-furnace gas has been tried for heating the open hearth furnaces, but not with much success, because its flame is not sufficiently luminous.

Coke-Oven Gas.—In coke ovens of the original bee-hive type, wherein coke is carbonised in large masses, a limited quantity of air is admitted to the oven, by which part of the coal is burned to supply the heat required to carbonise the remainder. In ovens of more modern types, the coal is charged into chambers 1 foot 6 inches to 2 feet 6 inches wide, 6 to 8 feet high, and 30 to 33 feet long, around the sides, bottom, and sometimes the top of which are passages of firebrick. These chambers are built close together in groups of 20 to 60, so that the brickwork surrounding each charge of coal is very considerable, and the heat lodged in this mass is sufficient to start the distillation of the Hydrocarbons contained in the coal. The gases given off are mixed with air, and burned in the passages surrounding the chambers containing the coal, and complete its carbonisation without admitting any air among the coal. In this way none of the fixed Carbon in the coal is consumed, and the yield of coke is, therefore, increased considerably. In some ovens the incoming air is heated by the outgoing waste gases, the gas distilled from the coal is drawn off, and the Ammonia oils, &c., are extracted before the gas is returned for use in the ovens, the by-products so recovered being of very considerable value.

In modern ovens, and with suitable coals, the gas given off may amount to as much as 8,000 to 10,000 cubic feet per ton of coal carbonised, and may represent as much as 15 per cent. of the heat contained in the coal. More is given off than is required to heat the ovens and supply steam to the stills, and the balance, which under favourable circumstances may amount to as much as one-half of the whole make of gas, is available for providing heat or power in an adjacent steel works. Until quite recently this supply of heat was practically allowed to go to waste.

The gas obtained is very rich, not differing materially from the gas made for illuminating purposes, and has about the following composition :—

Light Hydrocarbons, ...	1·5 to 3 per cent.
Methane, ...	25·0 to 35 „
Hydrogen, ...	50·0 to 55 „
Carbonic acid and Nitrogen, . . .	10·0 to 12 „

The gas varies considerably from moment to moment during the process of carbonisation, both in quality and quantity. During the first few hours after the ovens are charged the quantity is large and the quality high, but towards the end of the process practically none comes off, and that of very poor quality. Although the ovens are loaded and discharged in turn, so that the average volume and quality of the gas are maintained fairly constant, it is generally considered advisable, if the gas is required for use in gas engines, to instal a gasholder, so as to ensure a supply of gas as constant as possible, both in pressure and heating value, a condition necessary to ensure the regular running of the engines.

The average heating value of the gas is generally from 400 to 500 B.T.U. per cubic foot, according to the kind of coal used, but may, with some coals, be as low as 280 B.T.U. It contains enough Hydrogen and Hydrocarbons to give a high flame temperature when used cold and with cold air. Being free from tar and soot, which soon choke small passages conveying producer gas, and being supplied from a holder at a fair pressure, a considerable heating power may be carried through a small portable pipe. This makes it very convenient for heating unfired metal-mixers or ladles, for drying furnaces after repairs, or for heating Bessemer vessels and bottoms while in position.

Though the flame is much hotter than that of producer gas, it is not so luminous, owing to the absence of tarry matters, and, if used with it for heating open hearth furnaces, is liable to deceive the melter accustomed to judge the heat of the flame by its appearance on entering the furnace. While thinking he has not sufficient heat to melt his charge, he may be actually melting down the roof of the furnace.

Theory of Heat Engines.—Heat and mechanical work are convertible one into the other. The fall of 1 lb. weight through 778 feet (or of 778 lbs. through 1 foot) generates one British unit of heat, and conversely one British unit of heat is theoretically capable or raising 1 lb. weight through 778 feet. Thus the mechanical equivalent of one B.T.U. is 778 foot-pounds.

One horse-power is the work performed in lifting 33,000 lbs. through a height of 1 foot in one minute, or 1,980,000 lbs. 1 foot high per hour. Consequently, to obtain one horse-power per hour requires theoretically the supply of $\frac{1,980,000}{778} = 2,545$ B.T.U. per hour. For reasons to be explained later, the production of one horse-power always absorbs several times this amount of heat.

The conversion of heat into work, by any form of heat engine, whether steam engine, hot-air engine, gas, crude oil, or petrol engine, is only possible because a volume of any gas (or vapour, which is an unstable form of gas) expands or contracts as heat is imparted to or abstracted from it. The expansion or contraction amount to $\frac{1}{493}$ part of the volume which the gas occupies at 32° F. for every one degree of Fahrenheit rise above, or fall below, this temperature. Hence all heat engines, however apparently diverse may be their methods of operation, work on one common principle, may be compared on one common basis, and their efficiency measured by one common standard—namely, the proportion of the heat supplied to the engine which it converts into mechanical work.

So far as the capability of performing work is concerned, there is a strict analogy between the potential energy possessed by water raised to a high level of position, and gas or vapours raised to a high level of temperature. The work expended in raising water to any height above sea level, which is the zero of position beyond which water cannot fall, is returned in the form of mechanical work when the water is allowed to flow through a water engine, such as an hydraulic engine, water wheel, or water turbine; and the quantity of work done is the product of the quantity of water by the distance through which it falls while in the water engine.

Similarly, the work expended in raising a gas or vapour to any level of temperature above absolute zero (461° F. below freezing point), which is the zero of temperature below which temperature cannot fall, is returned in the form of mechanical work, when the gas (or vapour) is allowed to flow through a heat engine, such as a gas engine, steam engine, or steam turbine; and the quantity of work done is the product of the quantity of gas, by the distance through which its temperature falls while in the steam or gas engine. The water serves as the vehicle for the weight which performs work, and the gas as the vehicle for the heat which performs work.

The higher the level at which the water or heat is supplied, and the lower the level at which they are discharged, the greater the amount of work performed. Practical considerations fix the higher limit, while inevitable circumstances mainly determine the lower limit. For, just as, without consciousness of the fact, we are living in an atmospheric pressure of 14·7 lbs. above the absolute zero of pressure, when the barometer stands at 30 inches of mercury, so, without consciousness of the fact, we are living in a temperature of 493° F. above the absolute zero of temperature, when the thermometer stands at freezing point, or 32° F., and no means exist whereby we can cool the gases below the temperature of our surroundings, without a costly expenditure of power.

Whatever the proportion of the total conceivable range employed, that proportion only of the total energy contained in the lifted water or heated gas, can we even conceivably get back again from it. If the weight or the temperature fall through only one-third or one-eighth of the total possible distance, one-third or one-eighth only of the total potential energy contained in the water and gas respectively, can possibly be obtained from either of them. Even this proportion is reduced in practice by leakage of heat and pressure, friction of the moving parts, and other imperfections incidental to all mechanical appliances.

Taking absolute zero at 461° F. below the zero of the Fahrenheit scale, and calling the initial temperature to which the gas, steam, or other working fluid is raised, T, and the temperature at which it is rejected, T_1, the maximum efficiency of any heat engine even theoretically possible is, therefore, $\frac{T - T_1}{T + 461}$, all temperatures being measured by the Fahrenheit scale.

Theoretical Efficiency of the Gas Engine.—If the gas used in a gas engine must be manufactured expressly for it, nearly one-third of the heating power of the coal is used up in its production, most of it being absorbed in changing the fuel from a solid to a gaseous condition; only two-thirds of the heat units contained in the coal passes forward in the gas. But when the engine uses blast-furnace or coke-oven gases, which are by-products from other processes, this loss need not be considered.

In gas-engine cylinders temperatures have been recorded as high as 3,000° F. when working with blast-furnace gas, 3,700° F. with producer gas, and 4,250° F. with illuminating gas. The maximum temperature reached in the cylinder of a large gas engine working with blast-furnace gas is, however, usually about 2,600° F., but the temperature of the atmosphere into which the gases must be discharged is about 60° F., and, therefore, the maximum efficiency conceivably possible cannot exceed $\frac{2{,}600 - 60}{2{,}600 + 461} = 0{\cdot}65$, or 65 per cent.

In practice about 30 per cent. of all the heat supplied is carried away in the water used to keep the cylinder, piston, &c., sufficiently cool to enable the engine to be worked at all; 20 per cent. or so passes away in the waste gases through the exhaust pipe, because it is inconvenient, as will be explained later, to expand the gases down to atmospheric temperature. These circumstances reduce the actual thermal efficiency to 32·5 per cent.

But of this power developed in the cylinder from 15 to 35 per cent. is absorbed in the mechanical friction of the working parts, leaving only 27·6 to 21·1 per cent. of the potential power supplied by the gas available to perform work at the crank-shaft.

Theoretical Efficiency of the Steam Engine.—Reckoning the theoretical efficiency of the steam engine in the same way, the maximum pressure commonly carried in the boiler is 150 lbs. per square inch, which affords steam at a temperature of 366° F., and the minimum pressure into which steam can be discharged is a vacuum of about 2½ lbs. absolute pressure, answering to a temperature of about 136° F. Under these circumstances the efficiency of a steam engine cannot possibly exceed $\frac{366 - 136}{366 + 461} = 0{\cdot}27$, or 27 per cent.

But the steam has to be raised in a boiler fired with blast-furnace gas, and experiments made on good tubular boilers so fired show that only two-thirds of the heating power of the gas reappears in the steam raised in the boiler, which at once reduces the efficiency of the combined boiler and engine to 18 per cent.

Initial condensation, radiation, leakage, the practical necessity of releasing the steam while its temperature is still much above that of the condenser, and mechanical friction account for one-third of the power which could be developed in the cylinder, and leave a net power available for use at the end of the crank-shaft of only about 12 per cent. of the potential power contained in the gas.

Relative Actual Economy of Gas and Steam Engines.—Partly owing to the fact that the ready-made gas can be burned directly in the cylinder of the gas engine, while the steam engine requires the intervention of a boiler, and partly to the much higher initial temperature at which it can be worked, the gas engine will produce, from a given quantity of gas, fully two and a-half times as much power as a good compound condensing steam engine of fairly modern construction. One thousand cubic feet of washed and cooled blast-furnace gas will give in a gas engine, if fully loaded, 10 H.P. for one hour. The same gas used hot from the furnace with a good modern boiler will evaporate 62½ lbs. of water into steam at a pressure of 150 lbs. Allowing for loss by condensation in steam pipes, this will yield only 4 H.P., so that the gas engine will require only 100 cubic feet of gas per H.P.-hour to perform the same work as a steam engine consuming 250 feet.

Put in another way, 1,000 cubic feet of gas per hour, containing 100 B.T.U. per cubic foot, will supply 100,000 B.T.U. per hour. The thermal equivalent of 1 H.P. for one hour is 2,545 B.T.U., so that the heat contained in the gas is equivalent to $\frac{100,000}{2,545} = 39{\cdot}29$ H.P. per hour. A gas engine giving 10 H.P. with this quantity of gas is using 10,000 B.T.U. per horse-power per hour, with an efficiency of 25·45 per cent. A steam engine and boiler giving 4 H.P. would be using 25,000 B.T.U. per horse-power per hour, with an efficiency of 10·18 per cent., or allowing for the sensible heat in the gas if used hot about 25,500 B.T.U., which represents an efficiency of just about 10 per cent. Somewhat better results can be got both out of the gas and the steam engine, but these figures represent fair every-day practice with equally good plant in each case. Calculations showing that a gas engine will yield six times as much power as a steam engine are based upon comparisons between a modern gas engine and an antiquated steam engine and boiler.

Margin for Improving the Economy of Gas Engines.—The only means available for raising the efficiency of the gas engine is either to increase the initial temperature, or to expand the gases to a greater volume before opening the exhaust valve. The temperature of combustion within the cylinder is already that of molten steel, and the explosive pressure is 350 lbs. on the square inch, which may rise to over 500 lbs. in case the charge ignites prematurely before the piston has completed its compression stroke. With gases rich in Hydrogen and Hydrocarbons, such as coke-oven gas, the temperature produced by compression must frequently approach that of ignition, which is bound to occur when sufficient heat is generated by compression, the Diesel oil engine actually igniting its charge in this way.

Crossley Bros., of Manchester, endeavour to meet this difficulty, in some of their engines, by injecting a fine spray of water into the cylinder, which keeps down the temperature and pressure at the moment of explosion, the superheated steam formed raising the pressure to a corresponding extent towards the end of the stroke.

The question how far increased compression is possible is complicated by variations in the specific heat of gases at high temperatures—even dissociation might occur, when ignition was attempted, if pressures were unduly increased. Certainly more heat would be lost to the cooling water in the jacket, and more pressure by increased leakage. Experiments made by Professor Burstall have shown that, in certain circumstances, the thermal efficiency has actually declined when compression has been carried beyond 160 lbs. on the square inch.*

In any case a stronger and, therefore, more costly engine would be required to withstand the increased stresses to which it would be subjected, and it is doubtful if the capital charge on the greater first cost, and the additional wear and tear, would not, together, more than absorb the value of any gas saved by such a method of working.

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* *I. Mech. E.*, vol. i., 1908.

Many steel works managers consider that the commercially economical limit of compression has already been exceeded, and would prefer engines, the nominal power of which is based on a mean pressure of 60 or 70 lbs. rather than on 80 or 90 lbs., often used when rating the power of gas engines. The reserve of power and the reduction in trouble they value more than a small saving in what they regard as, in some sense, a waste product.

The other alternative, further expansion of the gas before release, involves a larger cylinder, with more cooling surface to extract heat, and a larger and, therefore, more costly engine; and so far as present experience goes, the additional cost increases out of all proportion to the saving of gas thereby effected.

The heat carried away in the jacket water, which has a temperature usually of about 110° to 130° F., can rarely be utilised for purposes outside the engine. That carried away in the waste gases has been employed to raise steam, 2 lbs. of water having been evaporated per horse-power developed in the gas engine, when working at full power; but if the load is variable, and the engine must run much of its time at light load, there is no margin worth mention. Sulphur and moisture in the gas are also very destructive to the boilers, and it seems doubtful if the attempts to utilise this source of waste are likely to justify the cost of the necessary apparatus.

There is little margin for improvement in gas engines on present lines, and unless some radical departure from existing practice can be devised—such, for instance, as the production of a workable gas turbine, which could dispense with the water-jacket and expand the gases down to atmospheric temperature and pressure, of which there seems no immediate prospect—we cannot expect to see the efficiency of gas engines much improved.

Margin for Improving the Economy of Steam Engines.—The efficiency of the steam engine can likewise be increased by raising the limit at which the heat is supplied to the engine. This can be done by raising the pressure carried in the boiler, but an increase in the pressure from 150 lbs. to 250 lbs. would only raise the temperature 37° F., and add to the wear and tear on the boilers; hence the employment of superheaters, whereby the temperature of the steam may be raised without a corresponding increase in pressure.

Like the gas engine, the steam engine suffers from the practical necessity for discharging the steam while much heat remains in it, above even the temperature into which it is possible to discharge it. The steam turbine has met this difficulty, and there is no margin now left for utilising the heat at the lower end of the scale.

By admitting superheated steam into reciprocating engines, and then passing it through exhaust turbines to a good condenser, the combination may afford, from a given amount of blast-furnace gas, half the power of a gas engine driven by the same gas, and this result is not likely to be improved on appreciably.

A conspicuous instance of what can be done by a combination of reciprocating steam engines and exhaust steam turbines is that of the electric generating engines of the New York Subway Power Station. These large engines, working with steam of 190 to 195 lbs. pressure, were giving out 4,600 kilowatts with a consumption of steam of 17·1 lbs. per kilowatt; and 7,500 to 8,000 kilowatts with 22 lbs. of steam per kilowatt. More power was wanted, so exhaust turbines were fixed between the engines and condensers, whereby the output was raised to 12,000 kilowatts with a consumption of 13·2 lbs. per kilowatt, and 16,000 kilowatts with 14·5 lbs. per kilowatt.

This corresponds to an output of 1 H.P. for only 9·4 lbs. of steam at the most economical point, which would represent, after allowing for condensation in the steam pipes, a consumption of about 165 feet of blast-furnace gas per horse-power per hour.*

The best steam engine throws away far more heat than it utilises, the cooling water from the condenser carrying away much more heat than the cooling water from a gas-engine cylinder, and the utilisation of the heat in this water is even more difficult.

Development of the Gas Engine.—The fact that whatever gas or vapour be employed the heat required to produce a unit of power must always—leakage and radiation losses neglected—decrease as the initial temperatures increase, has been quite well understood by all students of thermo-dynamics for the past 60 years. But if the water in a boiler was raised to much over 400° F. the pressure became dangerous, and hence many turned their attention to air as the working medium, which could be raised to much higher temperatures without necessitating such unmanageable pressures. The difficulty of using air is that its specific heat is so low that large volumes of it must be used, involving a large and costly engine, and the slow rate of transfer of heat through metal. The latter difficulty Ericson & Cayley attempted to overcome, by forcing the air through the furnace into the cylinder. The attempt failed commercially because of the rapid wear of the parts, and the impossibility of lubricating them at high temperatures.

It is not too much to say that neither superheated steam nor gas could be profitably employed in the cylinders to-day were it not for the introduction of mineral lubricating oils, which, having been distilled at very high temperatures, close on to a red heat, are not destroyed by the heat in the cylinder as any animal or vegetable oil would be.

The economy which theory clearly indicated must follow high initial temperatures was not attained until the fuel, in the form of a combustible gas, was ignited within a cylinder, which was kept cool by a water-jacket. In 1862 Beau de Rochas took out a patent for a gas engine, in which he laid down all the essential principles for successful operation, including a clear description of the advantage obtainable by compressing the charge before igniting it.

The first suggestion that blast-furnace gas could be employed for gas engines was made by Dr. Lürmann in 1886, but the credit for first demonstrating the fact in actual practice is due to B. H. Thwaite, who set to work at Wishaw, in 1895, a small engine of 14 H.P. using a rather rich clean gas. In the same year a small engine, driven by uncleaned gas, was started at Seraing, followed in 1898 by one of 200 H.P. working with partially washed gas. From that time onwards the advance has been very rapid, and in 1906 there were in Germany alone 385,000 H.P. of such engines. At present there are in daily use 1,000,000 H.P. of such engines in Europe, and 500,000 H.P. in America.

The Otto Engine.—When the use of blast-furnace gas in gas engines was first attempted, the form of gas engine in common use was the open-ended, single-cylinder, single-acting engine, working on the cycle patented by Dr. Otto in 1876, which carried out the principles laid down by Beau de Rochas 14 years previously. Many thousands of such engines, from 1 to 50 H.P., and some few rather larger, had been in successful operation all over the world for many years. Naturally this was the type of engine first tried.

Fig. 435 shows this engine in diagrammatic form. A is the gas valve for admitting gas, B the air valve for admitting air, and C the exhaust valve for getting rid of the burnt gases after use, and D the electric igniter. Imagine the engine to be running, due to the energy stored in the flywheel, and the piston to be as far in towards the back of the cylinder as it will go. The air valve has just been opened, and the piston on its way to the right sucks in air until the piston has travelled through a short portion of its outward stroke, when the gas valve is also opened, and a charge of air and gas is drawn in. The two valves are then shut, and the piston on its return stroke compresses the charge, and about the point where the piston is at the end of its return stroke, usually a little before this (the exact position depending upon the inflammability of the gas, and the speed with which the explosion is propagated within it), the charge is fired by means of an electric spark. The explosive pressure, which is almost instantaneous, drives the piston before it, and just before the piston reaches the end of its second outward journey the exhaust valve is opened; the piston then returns to its original position, and the exhaust valve is closed ready for the engine to commence a fresh round of operations. Thus the engine employs four strokes of the piston, performing four distinct operations to complete one cycle—(1) aspiration of the charge, (2) its compression, (3) its expansion after ignition, (4) its discharge after combustion, and is, therefore, called "a four-cycle engine."

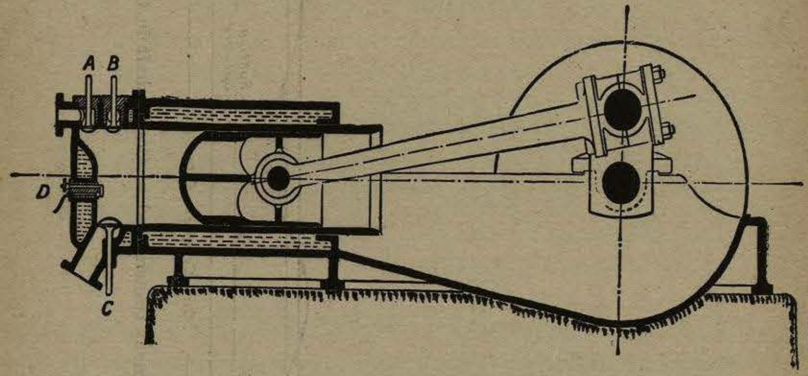

Fig. 435.—Otto Gas Engine.

Defects of the Single-acting Otto Engine.—This form of engine, very suitable for small powers, proved to have many drawbacks when the size was increased. Above 75 H.P. the exhaust valve had to be made hollow and cooled by a current of water pumped through it, or it soon warped and became useless, and above 150 H.P. the piston also had to be water-cooled, or various difficulties were occasioned. In large engines, the breech piece which contained the valves required to be 2½ inches thick to withstand the heavy explosive pressure employed; the flow of heat through such a thickness of metal was comparatively slow, and with a temperature of over 2,500° F. on one side and cold water on the other, unequal expansion led to frequent fractures of these necessarily complicated castings, even when made in steel.

The stresses induced in the crank-shaft by the cycle employed were excessive, and though this defect might escape notice in the case of small crank-shaft forgings, it soon made itself felt in the case of large ones. An inspection of the following diagrams will make this clear:—

Fig. 436 is an indicator diagram taken from an engine of this pattern,

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* *The Scientific American*, 24th Sept., 1910.

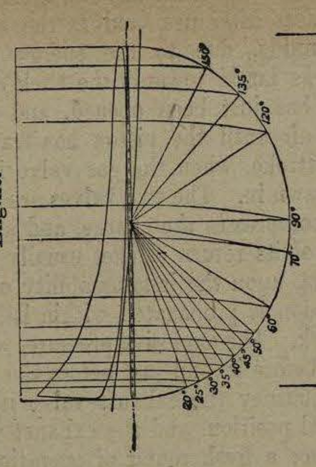

Fig. 436.—Diagram from Otto Gas Engine.

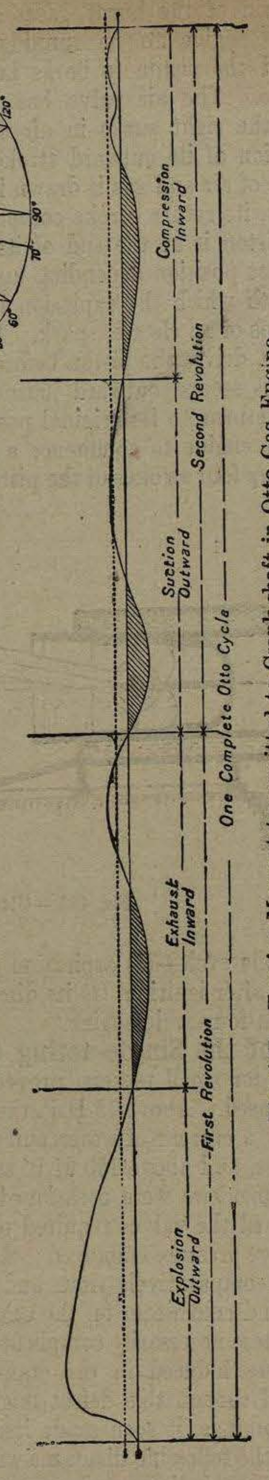

Fig. 437.—Turning Moment transmitted to Crank-shaft in Otto Gas Engine.

the sloped line representing to the same scale, the influence of inertia and momentum as explained on p. 668. The waved line in fig. 437 shows the twisting moment actually transmitted to the crank-shaft, after allowing for the influence of inertia and momentum. During the whole of the explosion stroke, the pressure behind the piston produces a forward twist on the shaft. But when the crank has passed the centre, and the return stroke commences, the crank, instead of being driven, has to drive before it the piston and connecting-rod, the inertia of which offers considerable resistance to motion during the first half of the travel; but after their speed has reached the maximum at the centre of their travel, the momentum stored in them assists the crank. Inertia and momentum play a similar part during the next three strokes, alternately retarding and accelerating the motion of the crank. The shaded areas below the line show the nature and extent of this reversal of stress in the shaft.

The power transmitted by any shaft is directly proportional to the mean turning moment imparted to it, but Wöhler's experiments show that fracture depends, not upon the maximum stress in one direction, but upon the total range of stress, and upon the frequency of its reversal. Useful work is performed in one stroke only out of every four, and, therefore, the forward maximum twist must be four times as great as in the case of a steam engine exerting the same power; and seeing the reverse twist is one-third of the forward twist with twice as many reversals per stroke, the crank-shaft requires to be about six times the strength of that required by a single-cylinder double-acting steam engine exerting the same power, as was proved by the experience of the Engine Insurance Companies, who at last absolutely refused to insure many large gas engines because of the weakness of the crank shafts.

The fact that the crank-shaft receives only one impulse in every four strokes, instead of one in every stroke as is common in steam-engine practice, causes the speed to vary considerably, a condition which is further aggravated when the method of governing employed was that originally introduced with this form of engine. This consists in occasionally cutting out an explosion altogether, when the speed of the engine exceeds the limits desired, which means that sometimes there is only one impulse in eight strokes, in which case the variation in speed is so noticeable that it needs no measuring instruments to detect it.

Such irregularities in speed may not be an insuperable objection when the engine is used to supply blast to the furnaces, but they render it quite unsuitable for driving electric alternators in parallel, the speed of which must not vary more than $\frac{1}{120}$ at any point of any revolution.

Two-cylinder Four-cycle Engines.—Two cylinders are occasionally placed to face each other, on opposite sides of the crank shaft, as in fig. 438, thus enabling twice the power to be exerted on the crank-shaft. They are known as vis-a-vis engines. The arrangement originally devised to avoid using stuffing-boxes for piston-rods, a difficulty successfully overcome by the present metallic packings, necessitates two impulses in one revolution and none in the next, thus adding little to the regularity of working, and it requires two connecting-rods and complete sets of reciprocating parts, so that during that revolution when no explosions occur the stresses induced by inertia and momentum are doubled.

A much more satisfactory arrangement is to place the second cylinder in tandem with the first, and employ only one connecting-rod, as in fig. 439. The explosions occur in each cylinder alternately, as the pistons make the out stroke, so that the crank receives one impulse in each revolution. As the explosion stroke in the one cylinder coincides with the suction stroke in the other, and as compression occurs in one or other of the cylinders whenever the pistons are making a return stroke, there is always a cushion to assist in bringing the pistons to rest on their return home. Reversal of twist on the crank-shaft, if not entirely prevented, is materially reduced, and the engine consequently runs much more smoothly.

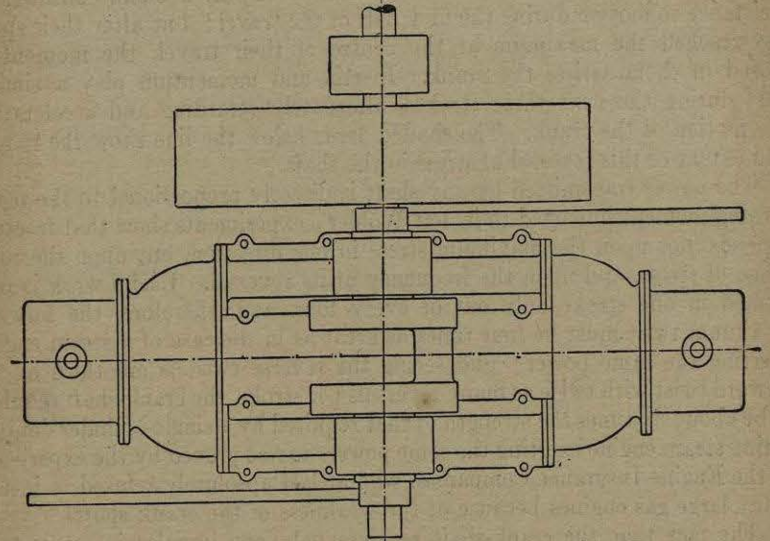

Fig. 438.—Vis-a-vis Gas Engine.

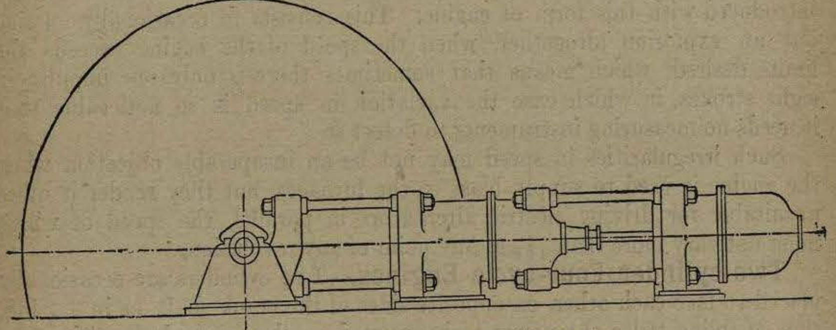

Fig. 439.—Tandem Single-acting Gas Engine.

Four-cylinder Four-cycle Engines.—By placing one pair of cylinders at each end of the crank-shaft, as in fig. 440, either of the above types of engine can be made to give two impulses per revolution, when the regularity and frequency of the impulses become exactly the same as that of an ordinary single-cylinder steam engine.

Double-acting Cylinders working on the Otto Cycle.—By closing both ends of the cylinder, as in a steam engine, placing two such cylinders in tandem, and firing a charge alternately in the front and back ends of one or other cylinder, one explosion and one compression stroke occur simultaneously. Before the middle of a stroke, while the pressure on the piston is excessive, the inertia of the reciprocating parts offers resistance to their motion, which falls off gradually to nothing at mid-stroke, where the pressure behind the piston has its mean value; then the momentum, just imparted to the piston and attached parts, comes into beneficial operation to assist movement and supply the deficiency of energy as the pressure falls. During this time the resistance to compression, exerted by the charge to be fired next, has been increasing, and at the end of the stroke, when the pressure driving the piston is released, it rises rapidly, and forms an excellent cushion to bring the reciprocating weights to rest. As a consequence the maximum pressure actually transmitted to the crank-pin is not much more than the mean of the pressure recorded by the indicator, and so inertia and momentum, which add to the shocks in the original Otto engine, in this case are utilised to prevent them. There is no reverse twist to be exerted by the crank-shaft and a general absence of knocking at the bearings, whereby the wear on them is reduced, and more silent running is secured. Friction is also reduced.

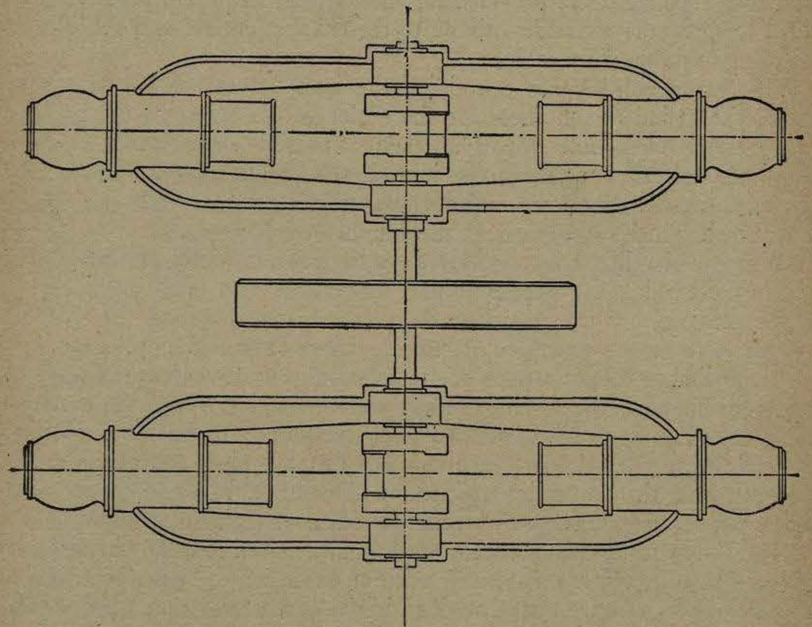

Fig. 440.—Four-cylinder Four-cycle Gas Engine.

In the single-acting single-cylinder engine the power for compressing the charge is first imparted to the flywheel and then taken from it again, just at the very instant when its speed is lowest, power being lost in friction at every bearing engaged in this double transmission during both operations. In the double-acting two-cylinder type, now under discussion, the power for compression is transmitted directly from the piston without the intervention of any bearings, and their frictional losses are avoided. Friction in the crank-shaft bearings, caused by the weight of the flywheel, is the same, whether the crank receives one or four impulses during the two revolutions, but in the latter case the proportion which this loss bears to the power exerted is reduced by three-fourths.

Regularity of rotation is ensured by the four equal impulses, and thus the anomalous result is achieved of an engine capable of giving out four