ON WENHAM'S HEATED-AIR ENGINE.

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The history of the Heated-Air Engine dates as far back as the year 1807, when Sir George Cayley invented his engine. This was followed by Stirling's engine, which was applied in 1818 to pumping water from a quarry in Ayrshire; but owing to the slight construction of the heating vessels, which were of boiler plate, the bottoms of the vessels were in a short time burnt through, and the invention was for a time abandoned. In 1827 however it was improved by the employment of compressed air, instead of air at atmospheric pressure, thereby reducing the size of the working parts without diminishing the power of the engine.

A diagram of Stirling's engine is given in Fig. 1, Plate 15. The two heating vessels A A have their lower ends exposed to the fire F, their upper ends being kept cool by means of water circulating round them. They contain the two plungers or displacers B B, attached to the opposite ends of a horizontal beam D, which is oscillated by a crank and connecting rod from the main shaft of the engine; these displacers do not fit the heating vessels, but have an annular space left all round them. The working cylinder C, containing a close-fitting piston, communicates at top with one of the heating vessels, and at bottom with the other. By the alternate upward and downward movement of the plungers B B the air in the heating vessels is displaced, and sent alternately to the bottom or heated part and to the top or cool part of the vessels; the air in either vessel thus becomes heated or cooled according as the plunger is respectively at the top or bottom of its stroke. A difference of pressure must therefore take place in the spaces above and below the working piston, which will consequently move in the direction of the lower pressure; and in doing so it changes the position of the plungers, and the operation is reversed. Two of these improved engines were constructed, one with a cylinder 12 inches in diameter and 2 feet stroke, which made 40 revolutions per minute and worked up to 21 horse power, consuming $2\frac{1}{2}$ lbs. of coal per indicated horse power per hour; and another in 1843 with a cylinder 16 inches in diameter and 4 feet stroke, making 28 revolutions per minute and giving 45 horse power. The latter was the celebrated engine of the Dundee Foundry, and did all the work of that establishment for upwards of three years, during which period no other motive power was employed. It was laid aside however at the end of that time owing to the failure of the heating vessels, which could not stand the heat they were exposed to.

While Stirling's improved engine was being brought out in this country, Ericsson produced his engine in America; and so much public confidence was obtained for it that a gigantic pair of marine engines of 600 horse power upon his principle were constructed for propelling the ship "Ericsson."

In all these heated-air engines, with the exception of Cayley's, a Regenerator, or more correctly speaking a Respirator, was employed for utilising that portion of the heat which would otherwise have been thrown away with the exhaust air; and this was the special invention of Dr. Robert Stirling. The regenerator consisted of a passage or chamber, filled in some instances with thin metallic plates or gratings, in some with copper wire or gauze, and in others with thin metallic tubes. Through this chamber the exhaust air was made to pass, and while traversing the interstices it deposited there a portion of its heat; the cold air subsequently introduced, traversing the regenerator in the opposite direction, took up the heat left in the metal. By this means the heat that would otherwise have been thrown away in the exhaust air was utilised for increasing the temperature of the incoming supply of air. In Ericsson's large engine the regenerator presented a heating surface of 4,900 square feet, and the copper gauze of which it was composed weighed 33,000 lbs. By this means it was expected to get back with the incoming air all the heat expended for working the engine, with the exception only of what was lost by conduction and radiation of the working parts: an idea bordering very closely upon perpetual motion. The heating apparatus was consequently made so inadequate to the requirements of the engine that this was the principal cause of its failure; moreover the metallic heating surfaces were in a short time destroyed in consequence of their direct exposure to the fire.

A diagram of Ericsson's engine is shown in Figs. 2 and 3, Plate 16. The working cylinder A is open at the top to the atmosphere and heated at the bottom by a furnace F, and is fitted with an air-tight piston B. Above it is placed the cylinder C of the air-pump, which is open at the bottom to the atmosphere, and has its piston D connected to the working piston B by four or more piston rods. The motion of the working piston B is transmitted to the machinery by the piston rod E. The air-pump draws in a supply of air through the inlet valve G, and discharges it through the outlet valve H into the receiver or reservoir of compressed air K. Underneath the piston B is attached a hollow box L filled with fireclay or other slow conductor of heat, the object of which is to protect the cylinder and piston from the more direct action of the heat. The cylinder inlet valve I, opened and closed by a cam, makes a communication between the reservoir K and the working cylinder A through one half of the regenerator M, which is a box containing laminæ of copper wire gauze; a similar outlet valve J opens the cylinder A to the exhaust N through the other half of the regenerator M. The action of the two halves M M of the regenerator is reversed periodically by means of the slide-valves P P after about every fifty strokes of the engine.

The working of the engine is as follows. The receiver K having been charged with air by a hand-pump through the pipe R to a pressure of about 10 lbs. per square inch above the atmosphere, the cylinder inlet valve I is opened; and air being thus admitted to the cylinder A through one half of the regenerator M, the piston B rises, and after a portion of the stroke has been performed, the inlet valve I is closed and the admission of air cut off, the remainder of the stroke being performed by expansion of the air by heat. During the upstroke the air-pump piston D forces a fresh supply of cold air into the receiver K for the next stroke. During the return stroke the cylinder outlet valve J is kept open, and the air is driven out of the cylinder A through the other half of the regenerator M and through the exhaust N into the air-pump cylinder C, depositing in its passage through the regenerator M the greater portion of its heat in the copper gauze, from which when the slide-valves P P are next reversed the heat is taken up by the incoming air from the receiver K.

The engines that have been described worked with great economy of fuel; but it is evident that to heat a bad conductor of heat, such as atmospheric air, large absorbent surfaces must be exposed to the fire, otherwise the amount of waste heat escaping into the chimney would be very great. The fact that so large a heating surface is required, and the impossibility of preserving metal plates constantly exposed to a very high temperature, and of maintaining them free from fracture and with tight joints, have caused engines upon that system to be abandoned.

The class of heated-air engines of which that forming the subject of this paper is a type consists of those in which the fire is enclosed, and fed by air pumped in beneath the grate in sufficient quantity to maintain combustion, while by far the largest portion of the air enters above the fire, to be heated and expanded; the whole, together with the products of combustion, then acts on the piston, and passes through the working cylinder; and the operation being one of simple mixture only, no heating surface of metal is required, the air to be heated being brought into immediate contact with the fire. The first successfully working engine on this principle was Cayley's, in which much ingenuity was displayed in overcoming practical difficulties arising from the high working temperature. The furnace was arranged so that the air pumped in could be conveyed above or below the fire as required; and before reaching the fire the air in its passage was conducted round an annular space between the firebrick lining and the outer casing of the furnace, so as to keep the exterior as cool as possible. The cylinder was surrounded by a water belt to avoid an excess of heat that would injure the packing of the piston. The cold air for working the engine was pumped in by a separate air-pump. One of these engines was kept at work for many months to test its capabilities: for economy of fuel compared with the work done it surpassed any form of steam engine known at that time; but the joints caused great trouble, and the cylinder and the piston packing were rapidly destroyed by the dust and particles of grit from the fuel, which acted as a grinding material and rendered lubrication impossible. An attempt was made to filter the air before entering the cylinder, by means of sheets of wire gauze; but these either gave way or were soon choked up, and so became useless.

The plan of enclosing the fire in the mass of air to be heated involves the utmost degree of economy, as there is nothing whatever lost in the absolute heating, and the products of combustion, varying in quantity according to the fuel employed, also add to the bulk of the mixture. These principles are embodied in the heated-air engine forming the subject of the present paper, which is the invention of Mr. Francis H. Wenham, the inventor of the binocular microscope, whose researches and inventions in many branches of science are of so much value. In this engine, which has been very successful for small sizes, a peculiar feature is that no separate air-pump is used, the top of the working cylinder itself being employed for that purpose. This is not a new idea, as Ericsson proposed utilising the top of the working cylinder in that way; but he never carried it out practically. The air-pump however must necessarily be of less capacity than the cylinder according to the degree of expansion required to be given by heating the smaller volume of air pumped in; and means had consequently to be devised for diminishing the capacity of the air-pump with the same diameter of cylinder, so that one piston packing might serve for both air-pump and working cylinder. This difficulty was overcome by the President of the Institution, Mr. C. William Siemens, who diminished the air-pump space by attaching to the piston a hollow trunk working through a stuffing-box in the cylinder-cover. Thus if the trunk were made one half the diameter of the cylinder, it would abstract one fourth from its capacity; and such an arrangement was employed in Mr. Siemens' regenerative steam engine, which would also work as an air engine or with air and steam combined.

Wenham's engine of one horse power is shown in Figs. 4 to 10, Plates 17 to 19. One of its special features is the furnace or air heater A, shown in section in Figs. 6 and 9, in which perfect combustion is obtained from ordinary smoking and bituminous coal; and coal of that description is preferred for this engine. The ashpit B or compartment under the grate is separated from the upper part by a moderately air-tight diaphragm, so that the air that is allowed to enter the ashpit is compelled to pass up through the firegrate. Above the grate is an annulus of segmental firebricks C C, shown in the sectional plan, Fig. 9; these bricks are made with semi-cylindrical grooves at their joints, so that when placed together, the centre forms a cylindrical hopper containing a store of fuel sufficient for several hours' consumption, and the grooves at the joints form a series of vertical flues or channels through the bricks. The column of coal descends as it is consumed on the furnace bars, and the air entering from the ashpit comes into contact with nothing but coal in a state of intense ignition; all the products of combustion have accordingly to pass through the ignited portion, and the channels or flues in the firebricks being also white-hot, no unconsumed products or smoke can escape through them. The furnace has a cover D in front of the ashpit, by which it can be hermetically closed; and there is a similar cover E at the top for filling the coal hopper. The products of combustion after leaving the channels of the firebricks C are met by a baffle plate F backed with fireclay, which prevents the cover of the furnace from getting unduly hot. The space between the firebricks and the outside shell of the furnace is filled to a level a little below the air passage leading to the cylinder with a slow conductor of heat, such as powdered brick or ashes, leaving an air space above that level.

There are two inlet air passages G and H, Fig. 6, for admitting the cold air to the furnace; the passage G conducts the air into the ashpit below the fire, and the other H leads above the fire; at their junction is placed a swing valve J, by which more or less of the air is directed below or above the fire. If all the air be directed below the fire through the passage G, the combustion will become very intense; the heat and consequent expansion of the air will become correspondingly great, and the engine will gain in power and speed. If on the other hand all the air be directed above the fire through the passage H, a very dull fire will be the result; the air will be comparatively cool, and will be less increased in volume, and there will be a diminution in the power of the engine. This difference of power is found to take place so instantaneously that the regulation of the air distribution serves as a very effective means of regulating the speed of the engine, and the governor K is consequently attached to the lever of the swing valve J; this arrangement is found to act so perfectly that no other regulation for speed is required, and it gives the advantage that the combustion of the coal is exactly proportioned to the amount of work performed.

The engine is of the vertical form, having two piston rods with the main or crank shaft running between them, as shown in the plan, Fig. 10, Plate 19; and in order to save space and render the cylinder M as compact as possible, the cylinder cover is made with a segmental recess or depression in which the crank passes, as shown in Fig. 6. The engine is single-acting, the upstroke only being made by the pressure of the heated air below the piston N, and the engine is carried through the downstroke partly by the expansion of the cold air compressed above the piston in the upstroke, and partly by the flywheel. The heated air from the furnace passes along the curved pipe Q, and is admitted at the bottom of the cylinder by the lifting valve L, which is opened by a cam P on the main shaft, as shown in Fig. 7; a lifting valve is required to be used, as a slide-valve will not answer. The exhaust valve R is of similar construction, and is also opened by another cam, as shown in Fig. 8; and both valves are closed by the spring S.

Q

In this engine the protecting drum under the piston N, Fig. 6, which was first brought out in America, is adopted for preserving the working surfaces of the cylinder and piston from the wearing action of the solid products of combustion. This drum is useful only in a single-acting vertical cylinder where the working pressure acts only on the underside. It is simply a prolongation of the piston, in length exceeding by a small extent the stroke of the piston, and is a little less in diameter than the cylinder, leaving a small annular space between the two. The packing ring of the piston being near the top, the dust cannot get to it, and the bright working part of the cylinder traversed by the packing ring is never uncovered or exposed to the direct action of the dust and heated gases. Any dust entering the cylinder from the furnace is blown out at the exhaust from the bottom. The piston is lubricated with dry plumbago powder, and in practice the cylinders are found to maintain a good working face, and to be as durable as those of steam engines; in fact it is found that a film of black-lead taking a high polish is continually being deposited upon the inner surface of the cylinder, and the cylinder has as great a tendency to diminish in diameter from this cause as it has to be worn larger by friction.

The chief peculiarity in this engine is the arrangement by which the top of the working cylinder serves as the air-pump, and is made to deliver into the furnace for expansion the reduced bulk of compressed air required for performing the work. At the top of the stroke the piston does not reach the cylinder cover, but a considerable clearance space is left between them, the capacity of which has been determined by experiment so as to give the best effect; the result arrived at is that the pressure in the furnace should never exceed 15 lbs. per square inch above the atmosphere. In the first portion of the upstroke the air contained in the air-pump is compressed to half its volume, or to a pressure of 15 lbs. per square inch, and not till then does there exist equilibrium between the air in the air-pump and that in the furnace; the delivery valve T then opens, as shown in Fig. 6, Plate 18, and during the remainder of the upstroke the air is pumped into the furnace. At the end of the stroke the valve T closes, leaving still 15 lbs. pressure in the space above the piston; and as there is no further escape for this, it acts upon the piston during part of the downstroke, and equalises the action of the engine to such an extent that a small flywheel only is required. This is not put forward as any advantage in power, because whatever force is required in order to obtain the pressure of 15 lbs. above the piston must be deducted from that of the upstroke; it is but transferred from the lower side of the piston to be utilised above it in the subsequent expansion of the compressed air. As soon as the air above the piston has expanded down to atmospheric pressure in the downstroke, the inlet air-pump valve U opens and admits the quantity of cold air required for the next stroke of the engine. By holding open this valve by means of a small hand lever placed below it, the cold air is merely pumped through it in and out of the air-pump, none going into the furnace, and the engine is thereby stopped. In order to start the engine, in the case of those of small size a few backward turns are given to the flywheel by hand, while the top cover is off the furnace; and from the arrangement of the valves it will be seen that when the flywheel is turned the reverse way the cylinder is converted for the time into a double-acting air-pump, forcing air into the fire during both the up and the down strokes of the engine; by this process the fire after lighting can be blown up and in a few minutes be ready for work; the furnace cover is then quickly replaced, and after a few forward turns given by hand the engine starts with the pressure due to the heating of the air in the furnace. In the larger engines it would be more convenient to charge the furnace with compressed air by means of a hand pump, in order to obtain a pressure with which to start.

With regard to the best capacity of the air-pump in proportion to that of the cylinder, it is found that air engines on this principle cannot be worked advantageously at a high pressure. In one experiment the capacity of the clearance space above the piston was diminished so as to give the air a pressure of 25 lbs. above atmosphere; but with this pressure the engine was found to work so much hotter that the heat generated by compression repeatedly set fire to the hemp packing in the glands of the piston rods; the working pressure had therefore to be reduced. If the air forced into the furnace, measured at atmospheric pressure, be equal to the cubical contents of the cylinder, or in other words if the air-pump and cylinder be identical in size, the force obtained from the expansion of the air by heat is so nearly absorbed in overcoming the resistance offered by the air during its compression in the air-pump that little or no power will be obtained from the engine. On the other hand if the air delivered by the pump, measured at atmospheric pressure, have only half the cubic capacity of the cylinder, the air will require an increase of 510° Fahr. (if taken in at 50° temperature) in order to double its volume and fill the cylinder at atmospheric pressure, the engine still giving off no power. The mean of these two extremes has therefore been taken, the capacity of the air-pump being made such that the volume of air forced into the furnace, measured at atmospheric pressure, is three-fourths of the cubic contents of the cylinder, the cushioning space above the piston at the top of its stroke being accordingly made equal to one quarter the capacity of the cylinder.

In Fig. 11, Plate 20, is shown the indicator diagram taken from one of these engines of 3 horse power, at a time when it was doing full duty with a friction break; the engine had a cylinder of 24 inches diameter with 12 inches stroke, and at the time the diagram was taken was making 108 revolutions per minute. From this diagram it is apparent that the exhaust was not quite so free in this particular engine as it should be, the downstroke showing too much back pressure at the commencement. The diagram shown in Fig. 12 is that of the air-pump, and represents the power required for compressing the air above the piston; it was taken immediately after Fig. 11, upon the same paper, by simply turning a three-way cock which shut off the passage to the bottom of the cylinder and opened that to the air-pump. In this air-pump diagram it will be seen that the line begins from the zero point on the left of the diagram, and gradually rises with the usual compression curve till it arrives a little beyond half stroke; during this time the delivery valve is not open, and no air is sent into the furnace. As soon as the pressure of the air in the pump begins to exceed that in the furnace, the delivery valve rises, and during the remainder of the stroke the compressed air is delivered from the pump into the furnace. When the piston arrives at the top of its stroke, the delivery valve closes; and when the piston begins to descend, there is a pressure of about 15 lbs. per square inch above it, and the body of compressed air being confined in a space of considerable capacity exerts a gradually diminishing force to about half stroke. In calculating therefore the force required to compress the air, this return pressure in the downstroke has to be deducted in the measurement of the diagram. The difference between the mean pressure in the pump, as shown in Fig. 12, and the mean driving pressure below the piston, as in Fig. 11, is 6·6 lbs. per square inch, which represents the effective driving pressure, as shown in the combined indicator diagram, Fig. 13. From the fact of the engine being single-acting with a large cylinder, the friction, as might be anticipated, is very great compared to the power; for it is found that while the indicated horse power, as shown by the combined diagram, Fig. 13, amounts to 9·76, the actual working power obtained at the friction break is only 3·30 horse power. This air engine has proved very successful for cases where a small amount of power is required, and has the advantage of working for long periods without requiring attention either for firing or for the engine, and with freedom from the risk of explosion or fire attending the use of a steam engine.

The actual temperatures of the air have now to be considered, first at its entrance to the cylinder from the furnace, and secondly upon leaving the cylinder at the exhaust after performing its work. The temperature of the air upon leaving the furnace was ascertained by one of Mr. Siemens' electrical pyrometers, which he most kindly placed at the author's disposal for the purpose of these experiments. The instrument was fixed into the curved pipe Q, Fig. 4, Plate 17, leading from the furnace to the cylinder, the pyrometer itself being inside the pipe, about half way between the furnace and the cylinder. A more convenient mode of measuring temperatures can hardly be imagined, the indicating instrument being placed in the office many yards from the engine to be tested, and connected with it by a conducting cable; thus the observer was far removed from any annoyance or heat from the engine, and all he had to do was from time to time to send a telegraphic enquiry to Mr. Siemens' "salamander," whose post was in the hot-air pipe Q, and an answer was instantly received giving the temperature of that great heat with perfect accuracy. From the average of a series of readings it was found that the air entered the working cylinder at a temperature of 1127° Fahr., equal to the dull red heat of an ordinary open fire. The average temperature of the air as it leaves the cylinder, ascertained by a mercurial thermometer placed in the exhaust port, was found to be 466° Fahr., a temperature at which steel acquires a pale straw colour, and about 16° above the melting point of tin. It thus appears that 661° is absorbed in doing the work, and 466° or nearly 40 per cent. of the whole heat is thrown away in the exhaust.

With regard to the consumption of coal, in these engines of one horse power it is found to be about 80 lbs. for ten hours' work, or 8 lbs. per horse power per hour. It thus appears that, even with the wasteful system of discharging the highly heated exhaust air, without any means of recovering the heat and utilising it by making it warm a regenerator through which the cold air delivered into the furnace from the air-pump might be passed, these engines can yet compete successfully with small steam engines in economy of fuel; and if a regenerator were added, and every arrangement were carried out to obtain the best theoretical effect due to air expanded by heat as a motive power, these engines would equal or surpass in economy of fuel the results of the best engines worked by steam. The difficulties met with are chiefly of a practical nature, and may be ultimately overcome, as several of them have been already in the engines now at work.

No allusion has been made in this paper to engines worked by gas, by gas and air, or by steam and air; in fact only those heated-air engines that seem to have played a characteristic part in the history of the subject have been described. When it is stated however that during the last half century upwards of 250 plans have been brought out for the application of air expanded by heat as a motive power, it will be seen how much attention the subject has received; but undoubtedly the first practical scientific application of the dynamical theory of heat is due to Mr. Siemens, whose name is so intimately and so honourably associated with the rise and progress of that great discovery of modern science. He was one of the very first who enunciated and demonstrated the conversion of heat into mechanical force, and in his regenerative steam engine a practical record remains of the strength of his convictions as to the truth of that theory at a time when it was received by only a few prominent physicists, such as Helmholz and Mayer in Germany, and Joule, Thomson, and the late Professor Rankine in this country; and it is an interesting fact, as showing the correctness of his reasoning, that Mr. Siemens' remarkable paper upon the conversion of heat into mechanical effect, though read before the Institution of Civil Engineers in 1853, just twenty years ago, is as much in accordance with modern scientific thought as if it had been written in the present year, and indeed contains nothing that new discoveries have not tended to confirm.

It now only remains to the author to acknowledge his obligations for the assistance rendered him in the preparation of this paper: to Mr. Wenham, for extensive notes and data supplied for the purpose; and to Mr. Siemens, to whom the author is indebted for much valuable information, and especially for the use of the very beautiful electrical pyrometer with which the temperatures were ascertained, and without which only a rough and scarcely approximate result could have been arrived at.

Mr. Cooke exhibited a model of Wenham's engine, and one of the engines was shown at work in the neighbourhood before and after the meeting, together with the Siemens electrical pyrometer by which the temperatures of the heated air were ascertained.

Mr. Wenham remarked that the time had fairly arrived when the soundness of the principle of using heated air as a motive power might receive some further consideration, as to the extent to which it could be practically applied and the best mode in which that could be effected; for the difficulties which had hitherto retarded the application of the principle had been chiefly of a practical nature. One of the main difficulties was the heating of the joints; if the engine now described were allowed to run for half an hour with extra work upon it, beyond what it was intended to do regularly, the great heat generated in the furnace and required by the engine to perform that work would cause the joints to start. This was a very serious matter in these engines, for it was their peculiarity that they would not bear the slightest degree of leakage; a definite measure of air was taken into the engine at each stroke, and the smallest leakage was therefore perceptible at once in a reduction of pressure; the falling of the governor then caused an increased proportion of air to pass underneath the firegrate, thereby augmenting the heat and further aggravating the evil.

With regard to the fuel used, the best kind of coal for raising steam was not found to be the best for this engine; but very inferior bituminous descriptions could be used with advantage, particularly if containing a considerable quantity of moisture. This had suggested the idea that for keeping the engine cool it would be well to inject a small quantity of water into it; but there was a difficulty in doing so, because when the engine was left standing and had got cold, the interior of the cylinder became corroded by the moisture, and it would be difficult to start the engine again. He thought however it would be well for the air to be introduced into the engine in a moist condition, or that some means should be provided for supplying moisture to it above the fire; and he understood experiments were now being made with this engine with that object in view.

For lubricating the piston, oil was first used, as the top of the cylinder did not get hot, but continued cool enough after a day's work to bear the hand on it; but though the oil remained fluid while the engine was working, it got clogged as soon as the parts became cold, and this seemed to be a fatal objection, requiring the cylinder to be carefully cleaned out every day through a lid in the top cover. Plumbago was then tried and answered extremely well, and he had never known a case of the cylinder scoring when lubricated with plumbago. The dry plumbago powder was blown into the cylinder above the piston opposite the air passage, and the rush of cold air entering the top of the cylinder rather tended to sweep the plumbago backwards; the powder gradually worked its way round the circumference of the piston, and covered the cylinder with a bright coating, which rendered it quite as durable as the cylinder of a steam engine.

Mr. E. J. C. Welch mentioned that in making experiments six years ago with Edwards' hot-air engine one of the chief difficulties he had met with was the distortion of the working parts from the engine getting too hot; the longer it worked, the hotter it became, and the working parts getting out of square caused friction enough to stop the engine. The lubrication of the piston had been a source of trouble, the packing being made simply with three ordinary rings; plumbago alone was tried first, and then a mixture of plumbago and soapstone, which was found to lubricate more effectually than plumbago alone. When the engine got too hot, leakages arose, and a very slight leakage of air was sufficient to bring the engine to a standstill; nor did there seem to be any means of supplying by an extra large air-pump sufficient air to compensate for these ordinary leakages; the door of the furnace was ground on in its seat, and every precaution taken to prevent leakage, but without success. Another difficulty had been that particles from the ashes carried over from the furnace got under the air valves and prevented them from closing completely; anything that caused the valves to stick was of course fatal to the working of the engine, and he had therefore tried an equilibrium slide-valve, instead of the flap valves, and found it worked satisfactorily. He had had an engine made with a cylinder of only 6 inches diameter, and with a separate pump to maintain the supply of compressed air; but though carefully made, the friction in so small an engine was found to absorb all the power that could be generated.

Mr. Wenham said the smallest size made of his engine had a cylinder of 12 inches diameter, and the effective power developed by it as measured by a friction break was half a horse power. He had never experienced any trouble from ashes getting under the valves in any of the forty engines that had now been constructed and put to work; the valves came down heavily in closing, and would stamp to a fine powder any particles of ashes lodged upon the seats, nor had he ever known the engines miss a stroke and stop from this cause in consequence of any of the valves sticking partly open.

Mr. J. McFarlane Gray observed that the indicator diagram from the heated-air engine furnished an explanation of the reason why such an engine of small size, say with a cylinder of even as much as 6 inches diameter, would be prevented from working by the excessive friction. For the production of the greatest amount of power, the object in any engine was to get the full part of the indicator diagram as near the middle of the stroke as possible, the leverage of the crank being there the greatest; while near the ends of the stroke, however great the pressure upon the piston, a large percentage of the power was lost by friction. The diagram now exhibited however showed a considerable effective pressure acting upon the piston at the two ends of the stroke, but scarcely any in the middle, on account of the back pressure of the compressed air above the piston at that time being equal to the driving pressure of the heated air below the piston. Moreover it appeared from the diagram that the mean effective pressure throughout the stroke was only 6·6 lbs. per square inch, and as the engine was only single-acting instead of double-acting this was equivalent to only 3·3 lbs. average pressure in each stroke, which again was reduced to 2·3 lbs., as the friction could not be estimated at much less than 1 lb. per square inch on the piston. Considering that in a steam engine the average effective pressure in each stroke was very commonly as much as 20 lbs. per square inch, the balance in favour of steam appeared to him to be very great.

Moreover on comparing the expansion curve of air with that of steam, when expanding heated air in the working cylinder of an engine, it was found that, starting in each case with an equal volume and pressure, the utmost additional theoretical effect that could be obtained by the expansion of the air to infinity would be only 2·45 times the work done by the air acting without expansion; whereas with steam indefinitely expanded the theoretical additional effect would be about 9 times the work of full pressure, showing an advantage of more than three to one in the expansion of steam as compared with that of air. This great difference in favour of steam was frequently lost sight of he thought in considering the relative capabilities of steam and caloric engines, and appeared to him to recommend steam as the most peculiarly advantageous medium for transforming heat into work.

Mr. WENHAM mentioned that some experiments he had made in expanding the air within the cylinder of the engine had not been productive of any beneficial results in practice, because the initial pressure of the air was so low that the benefit of the expansion was not appreciable; and to carry out expansion to such an extent as materially to increase the power of the engine would have involved so great an increase in size of cylinder that it had not been attempted.

Mr. E. A. COWPER had seen Ericsson's first caloric engine in 1834, as well as his second one of 24 horse power made shortly afterwards, and many others by different makers; and although Ericsson's 24 horse power engine undoubtedly worked pretty fairly at times, and with a small fire, it did not keep in order long, and on the whole was very unsatisfactory, though much money was spent on it by Mr. John Braithwaite, with whom he himself was then articled. It was a very complete pair of engines, with cranks at right angles, and a large and a small cylinder to each engine. The engine worked a horizontal double-acting pump, 30 inches diameter and 3 feet stroke, and drove the water over the top of a standpipe some 20 feet high; and in order to give it more work to do, a loaded safety valve was added at the top, and the pump had to drive the water out under this valve. The theory of the caloric engine was to heat a certain quantity of air, and, after a certain amount of work had been obtained from its expansion, to absorb the remainder of the heat from it and utilise this for heating another charge of air; and both Stirling's and Ericsson's engines had been constructed with the idea of recovering and using over again the heat still left in the air after doing work in the engine. Several caloric engines that had been designed from time to time had not been made to save the heat left in the air after use, and this would seem to be a source of great loss; possibly some arrangement could be added to the engine described in the paper to do something in this way, so as to reduce the very heavy consumption of fuel that had been named, though of course it was not wise to burden an engine so small as only 2 horse power with much complication. He believed the difficulties increased greatly when caloric engines were made at all equal in power to ordinary sized steam engines, and these practical considerations had always deterred him from attempting to do anything in the way of making a caloric engine. He should like to mention that in some marine steam engines 1 indicated horse power had now been obtained with a consumption of only 1·3 lbs. of coal per hour, by expansive action in two cylinders carried to a high degree; and although the theoretical minimum consumption could never be reached in practice, he hoped the actual consumption might yet be reduced still further than it had at present been.

The PRESIDENT enquired what sizes had been made of the engine described in the paper, and what was the smallest size that was considered advisable.

Mr. WENHAM replied that the engines had only been made of three sizes, with 12, 15, and 24 inch cylinders; several engines of the largest size were now at work, and some of them had been in use as long as five years. The manufacture of the smallest size, with 12 inch cylinder, which had been of half a horse power, had now been quite abandoned, because it cost nearly as much to make an engine of that size as the one horse power engine with 15 inch cylinder shown in the drawings; and as the size increased he had no doubt the engines would prove more economical and effective. For a large power it might be better to have two cylinders of half size, instead of a single large one. The main point was to keep down the heat from the furnace, so as avoid risk of injuring the joints, and with this view the later engines had been made with a larger area of firegrate and a smaller combustion chamber. Refuse slack of Welsh coal had been burnt in these engines until nothing was left but a cake of slag.

Mr. W. E. Newton enquired what was the power of one of these engines with 24 inch cylinder; and whether any further information could be given relative to the consumption of coal per horse power.

Mr. Wenham replied that the 24 inch cylinder engine was of about 4 horse power. He had not obtained any further particulars relative to the consumption of fuel than those given in the paper, a one horse power engine working for ten hours on a consumption of 80 lbs. of coal, which was equivalent to 8 lbs. per horse power per hour. There was a slight difference in the working of the engine in summer and in winter, rather more power being developed in cold weather on account of the greater density of the air taken in.

Mr. C. E. Amos remembered that at one of the meetings of the Royal Agricultural Society one of Ericsson's engines had been exhibited by Messrs. Ransomes and Sims, and the experiments then made with it showed that the amount of power given out was remarkably small for so large an engine, while the consumption of fuel was very large, amounting to about 18 lbs. of coal per horse power per hour; he did not know what became of that engine afterwards. Some years subsequently another heated-air engine had been exhibited at Vichy in France; and application having been made to himself to construct a larger engine on the same plan, he had had the original engine brought over to this country for the purpose of ascertaining its actual performance, and had found that, though developing as much as 8 horse power, it gave out an effective result of only $1\frac{1}{4}$ horse power at the flywheel, the remaining $6\frac{3}{4}$ horse power being absorbed by the engine. Such an engine if applied to locomotive purposes, as had been contemplated, would have required a whole train to carry the cylinders necessary for producing the requisite power; and he had accordingly declined to have anything further to do with it. With respect to the hot-air engine described in the paper, it was to be observed that it had the advantage of being perfectly safe from explosion or from any danger of fire, and might be handy for purposes where not much power was wanted, such as for a pumping engine on a country estate; he believed however that great improvements would have to be effected before any hot-air engine could be brought into comparison with a steam engine for general use.

The PRESIDENT said that many years ago he had given much attention to the question of obtaining from heat a larger proportion of mechanical effect than had previously been realised. With regard to the best medium to be employed for the purpose, although on theoretical grounds this was immaterial so long as no heat was thrown away, there were many important considerations in favour of steam, which had a higher rate of expansion by heat than air, and did not involve the employment of an air-pump for producing a supply under pressure. By the application of the regenerative principle he had obtained in small steam engines satisfactory results upon the whole; fifteen or sixteen engines altogether had been made on that plan, of from 5 to 10 horse power, and had worked for a series of years with very fair results. One of them had been put to work in Paris, and had been examined by Gen. Morin and M. Tresca, and in a whole day's working the consumption of coal had been found to be 1·67 kilos. or 3·68 lbs. per break horse power per hour. But on attempting to carry out the same plan in engines of larger size, of 20 horse power or more, difficulties had arisen in every direction, which had compelled him to relinquish the endeavour. One difficulty had been that mentioned in the paper with regard to the joints; and he had found that the best joint to resist a high heat was made by turning a number of concentric grooves in the faces of the flanges, and filling them with a cement composed of fine dust of cast iron mixed with white and red lead previously mixed up with linseed oil, and worked into a very stiff cement that set as hard as iron when exposed to heat; by that means he had succeeded in making tight joints. But what had discouraged him at that time was the result he had arrived at in preparing a paper* to which reference had been made, "On the conversion of heat into mechanical effect." In considering what would give a proper conception of a really perfect engine, he came to the conclusion that if steam were generated at such a pressure as to occupy only the same bulk as the water itself, and were then expanded down until it was all condensed through expansion, the utmost effect theoretically possible would thereby be obtained, because the whole of the heat would have been converted into mechanical effect. In the accompanying diagram of a portion of the dynamical expansion curve of steam, the shaded rectangle showed the utmost power that could be obtained in a condensing engine with perfect vacuum using steam without expansion, and the result was found to be that wherever this rectangle was taken its area amounted to only 1-10th of the area of the curve expressing the power due to the ultimate expansion of the same steam; but a good high-pressure expansive engine using steam of four or five atmospheres total pressure, cutting off at about one tenth of the stroke and working down to a good vacuum, realised a very

* (See Proceedings of the Institution of Civil Engineers 1852-53 page 571). In the Steam expansion curve shown in Fig. 15, Plate 21, the horizontal scale gives the volumes of steam compared with the volume of the water from which it is produced; this is the correct dynamical expansion curve of saturated steam allowing for the loss of the heat that is converted into mechanical effect when the steam is expanded behind a working piston; the shaded area, or any other rectangle drawn to the curve, represents the power obtained from a condensing engine with perfect vacuum but without expansion. In the Air expansion curve shown in Fig. 14, Plate 20, the horizontal scale gives the volumes of air compared with the volume of an equal weight of water; the dotted curve is the hyperbolic expansion curve of constant heat, representing Marriotte's law that the pressure and volume are inversely proportionate to each other; and the full curve represents the actual rate of expansion, showing the reduction of temperature during expansion, and the consequent contraction of volume; this curve is in accordance with the observed fact that, when air at any pressure and at the temperature of 32° Fahr. is compressed to double its original pressure, its temperature is raised 70° Fahr.

considerable proportion, something like one fourth or one fifth of the theoretical maximum which could ever be obtained. The theoretical minimum consumption of fuel in a perfect steam engine he had calculated would be (taking 14000 as the total units of heat developed by the complete combustion of 1 lb. of carbon)

$$\frac{33000 \text{ ft.-lbs.} \times 60 \text{ mins.}}{14000 \text{ units heat} \times 772 \text{ ft.-lbs.}} = 0{\cdot}2 \text{ lb.}$$

or one fifth of a pound of carbon per horse power per hour; or one fourth of a pound of coal, taking into account impurities.

In the case of the air engine, it was apparent that both Stirling and Ericsson had over-estimated the real value of the regenerator under a misconception of its true action; they had imagined that it was possible to absorb and give back the whole of the heat originally put into the air, with the exception only of accidental losses, and had overlooked the fact that a portion of the heat became entirely used up by being changed into mechanical effect; both their engines had accordingly been deficient in heating power, and had failed to give permanently satisfactory results. Even supposing perfect reabsorption of heat from the exhaust air, theoretical considerations showed that an air engine was necessarily very imperfect as a means of developing power from heat; because although a volume of highly compressed and highly heated air, if expanded down to atmospheric pressure and discharged at no higher temperature than that of the external atmosphere, would yield the full result for the heat absorbed in expansion, yet an equal weight of air would then have to be taken up again and compressed to the original pressure, thereby generating a great amount of heat, which would all be wasted because it was generated in the air before its expansion by heat took place and when it should occupy the least volume, the power of the engine being dependent upon the increase of volume. In the best air engines therefore, even supposing perfect absorption of the escaping heat, it would not be possible to realise anything like so much as one fourth or one fifth of the theoretical maximum of mechanical effect due to the heat put into the air. Another drawback was that in most air engines, and particularly in Stirling's, owing to the low conducting power of air and insufficient amount of heating surface, the cylinder or vessel in which the air was heated by the fire was found to get fully red-hot, so that the products of combustion reached the chimney at that elevated temperature. This source of loss was obviated in the engine described in the present paper, by causing the products of combustion to pass through the working cylinder, the air being heated by direct contact with them; and if the expansion in the cylinder could be carried far enough, no doubt the whole of the heat in the products of combustion might in this case be utilised; but it was clearly impossible to carry expansive action very far in this engine, owing to its low working pressure, and moreover the working of the air-pump constituted a very heavy loss of useful effect. The loss of sensible heat escaping at the exhaust might be remedied by the application of a regenerator; but this could not be done except at a sacrifice of the simplicity of construction which appeared to him to constitute the chief recommendation of the engine. It was impracticable he believed to carry out the principle of the hot-air engine on a scale sufficient to give any large amount of power; but a question of much practical importance was to produce a safe engine of small power, which could be put up anywhere, in any room, because requiring no boiler, and therefore necessitating no increased rate of insurance against fire. This object had been already accomplished by various constructions of gas engines, and was also effected by the hot-air engine now described, which he hoped would be so far perfected in its details as to give an effective power of as much as 4 or 5 horse power; and even though the consumption of coal were not reduced below 8 lbs. per horse power per hour, there were no doubt many cases in which such a source of motive power could be advantageously employed.

He moved a vote of thanks, which was passed, to Mr. Cooke for his paper, and also to Mr. Wenham for the additional information he had kindly given.

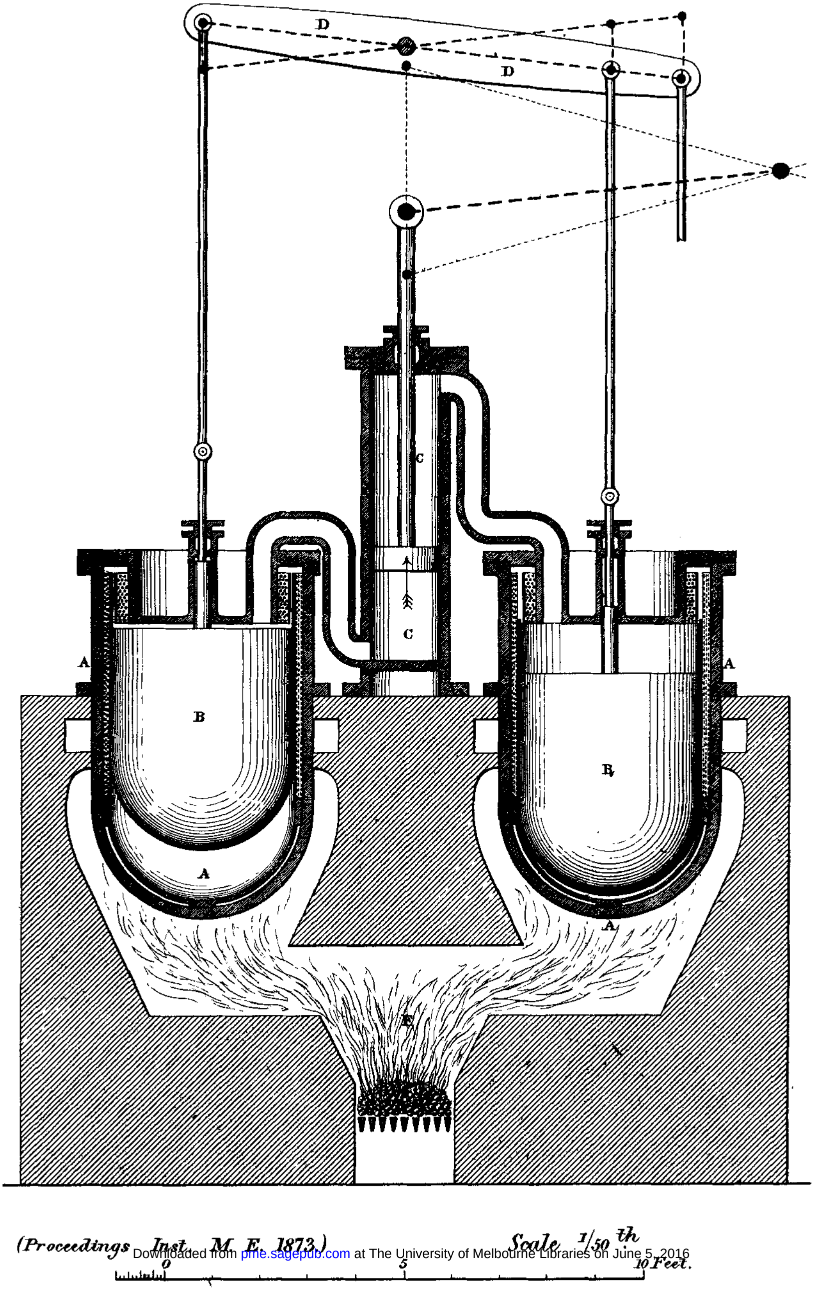
The PRESIDENT proposed a special vote of thanks, which was passed, to the President and Council of the Institution of Civil Engineers, for their great kindness in granting the use of the rooms of the Institution for the occasion of the present Meeting.

Mr. HAWKSLEY, the President of the Institution of Civil Engineers, acknowledged the vote of thanks.

The Meeting then terminated.

HEATED AIR ENGINE. *Plate 15.*

Fig 1. *Diagram of Stirling's Engine, 1843.*



(Proceedings Inst. M. E. 1873.) *Scale 1/50 th*

Fig. 2. *Diagram of Ericsson's Engine, 1853.*

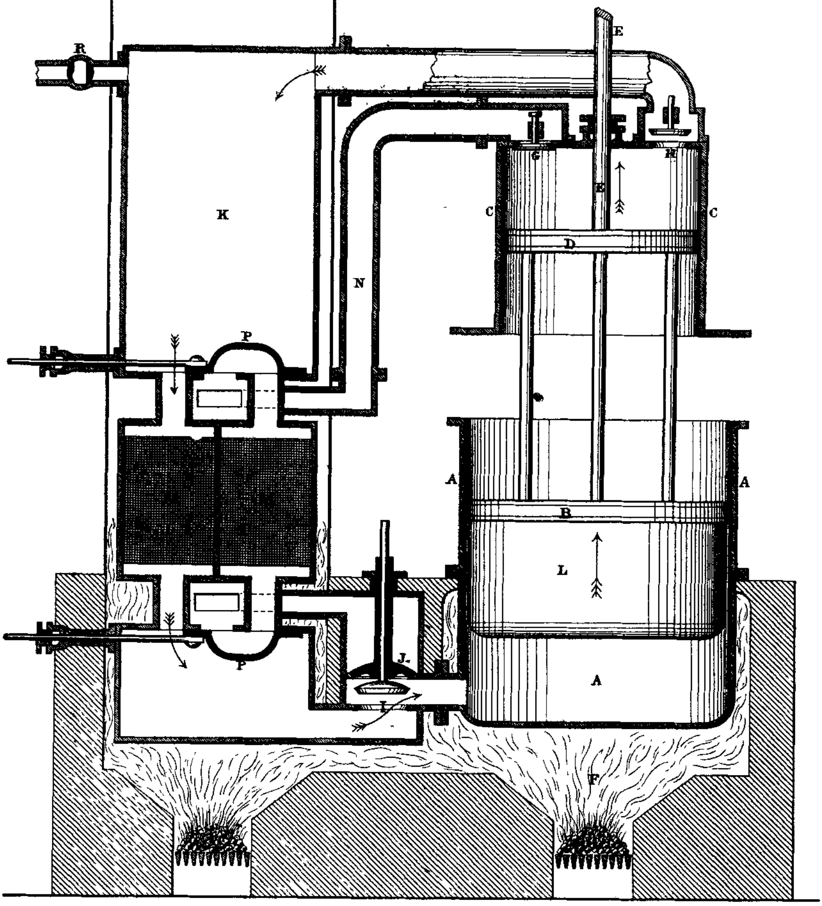
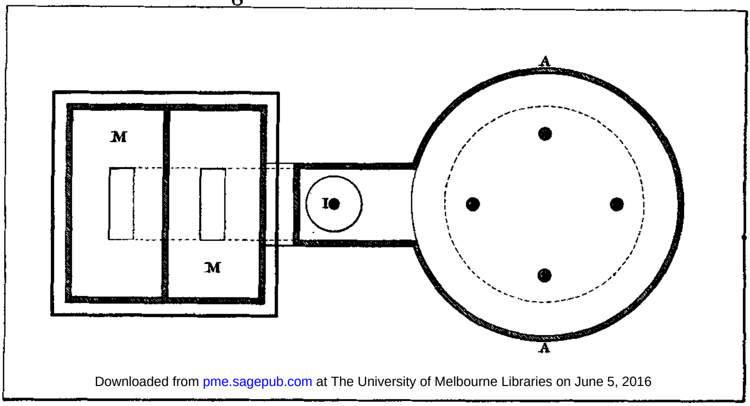


Fig. 3. *Sectional Plan.*



 Scale 1/120 th

HEATED AIR ENGINE.

Wenham's Engine.

Fig. 4. *Side Elevation.*

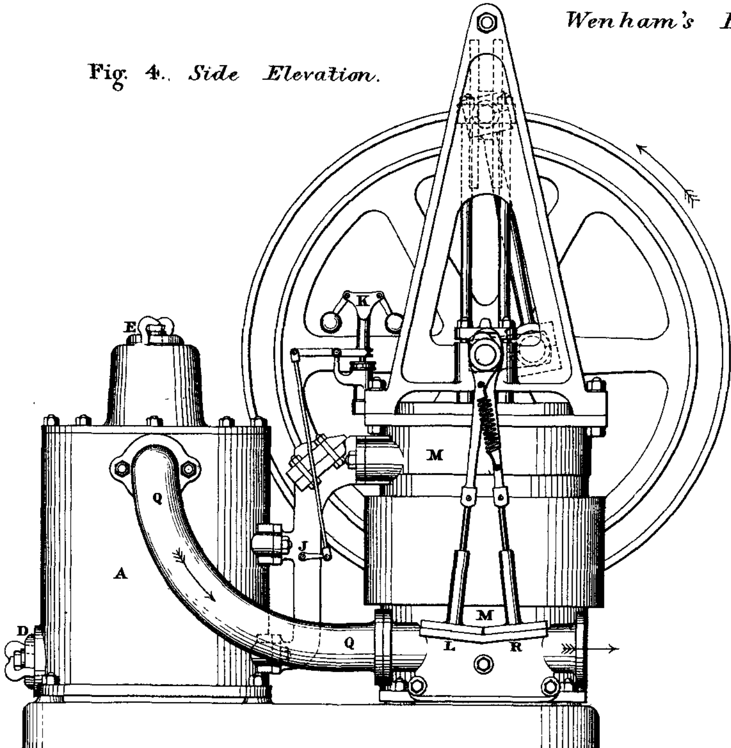
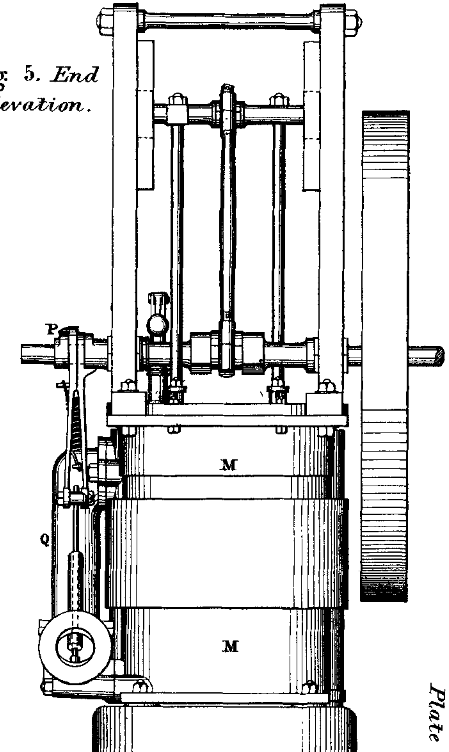


Fig. 5. *End Elevation.*



(Proceedings Inst. M. E. 1873.) *Scale 1/10th*

Ins. 12 6 0 1 2 3 4 Feet.

HEATED AIR ENGINE.

Wenham's Engine.

Plate 18.

Fig. 6. *Vertical Section.*

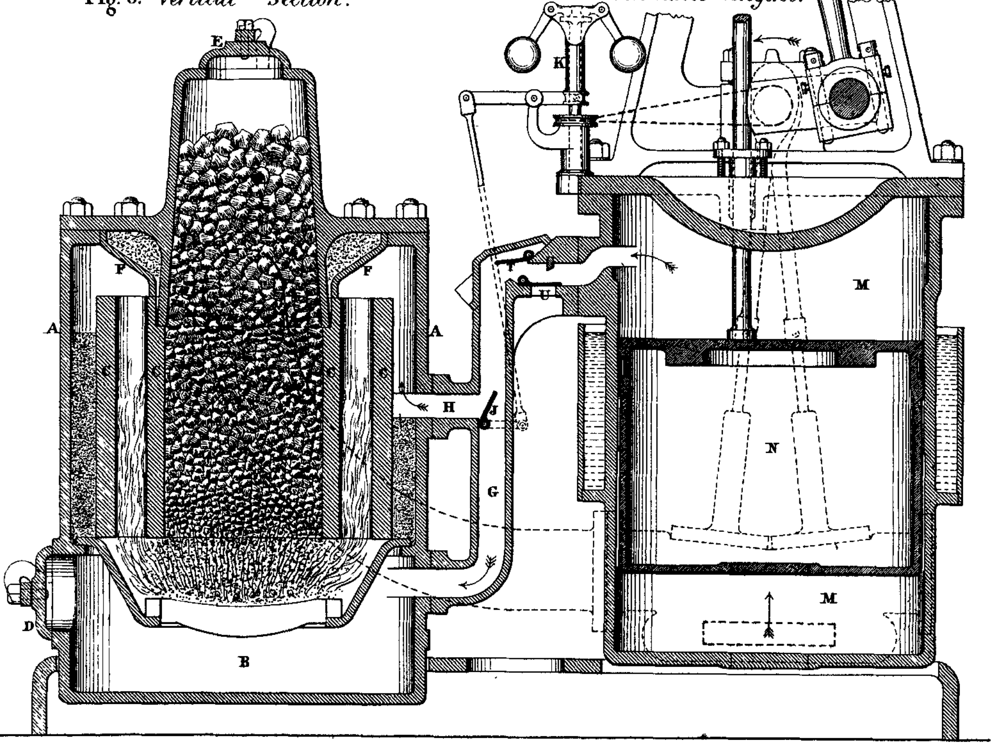
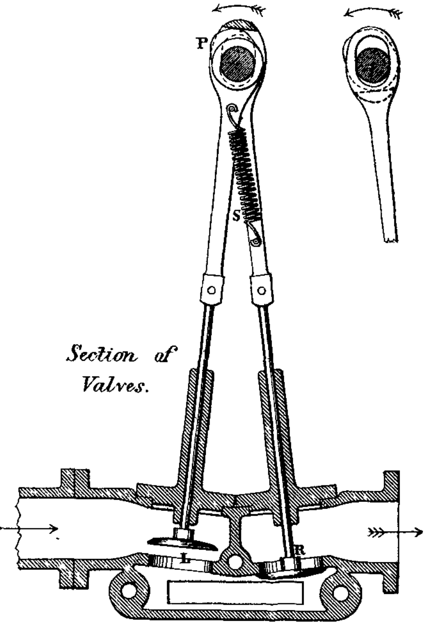


Fig. 7. Fig. 8.



Section of Valves.

(Proceedings Inst. M. E. 1873.) *Scale 1/10 th* 0 10 20 30 *Inches.*

Plate 18.

HEATED AIR ENGINE.

Plate 19.

Wenham's Engine.

Fig. 9. *Sectional Plan of Furnace.*

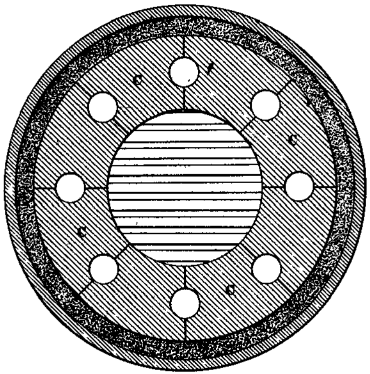


Fig. 10. *Plan.*

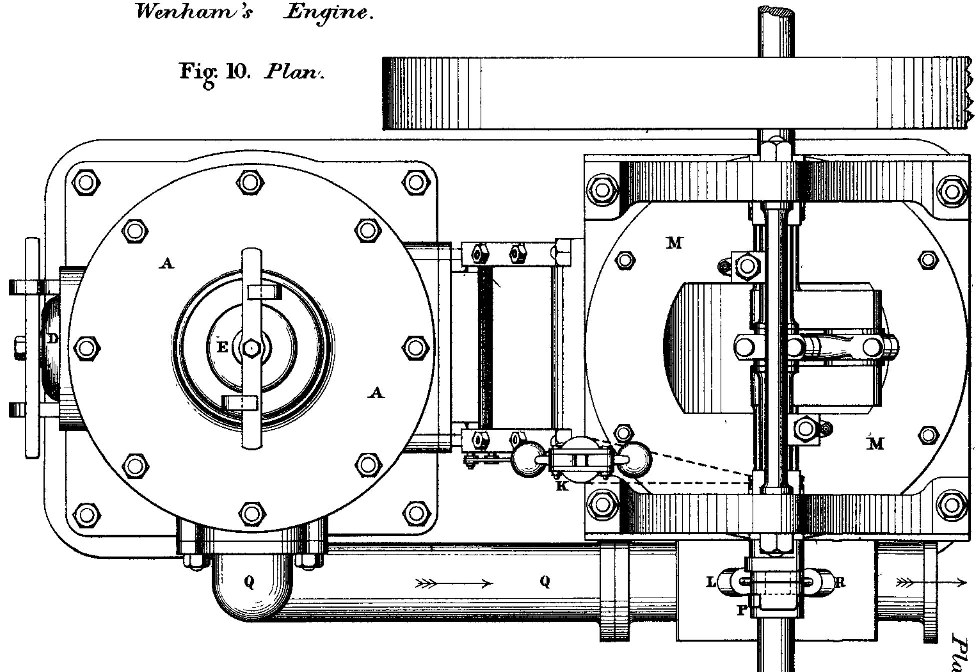


Plate 19.

(Proceedings Inst. M. E. 1873.)

Scale 1/10th. 0 10 20 30 *Inches.*

Fig. 11. *Indicator Diagram showing Driving Pressure below piston.*

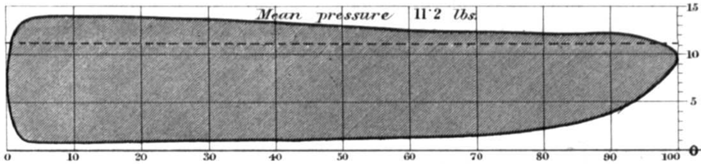


Fig. 12. *Indicator Diagram showing Air Compression above piston.*

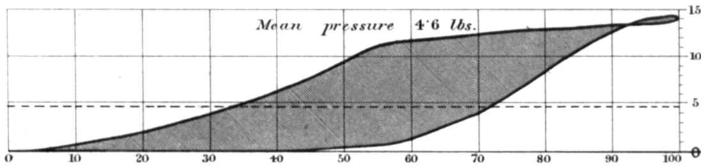
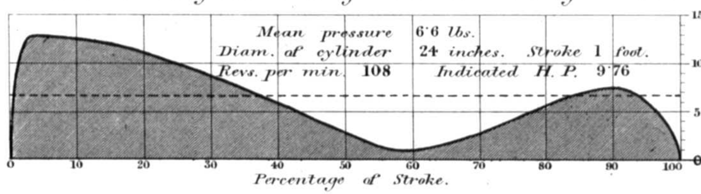


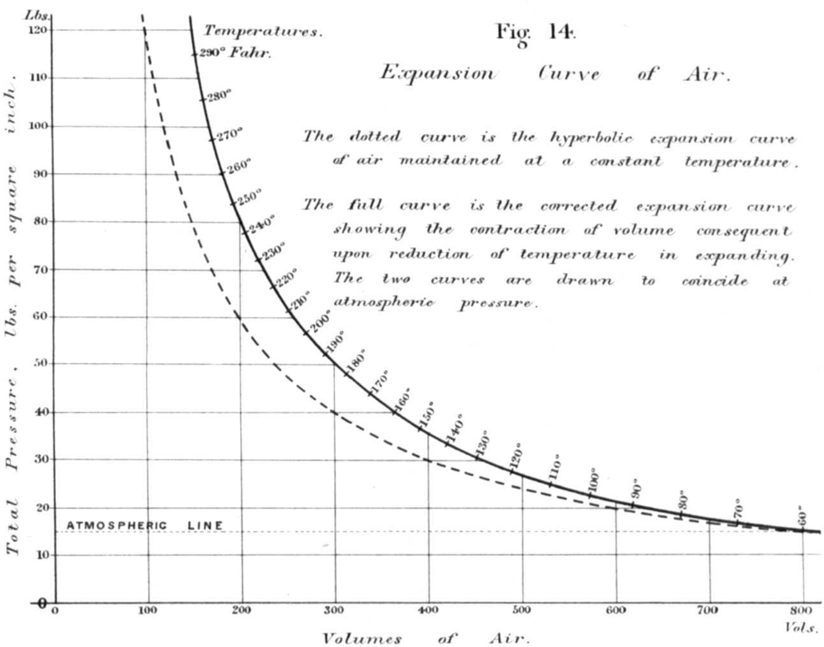
Fig. 13. *Combined Diagram showing Effective Driving Pressure.*



Pressure above atmosphere, lbs. per square inch.

Fig. 14.

Expansion Curve of Air.



The dotted curve is the hyperbolic expansion curve of air maintained at a constant temperature.

The full curve is the corrected expansion curve showing the contraction of volume consequent upon reduction of temperature in expanding. The two curves are drawn to coincide at atmospheric pressure.

(Proceedings Inst. M. E. 1873.)

HEATED AIR ENGINE.

Plate 21.

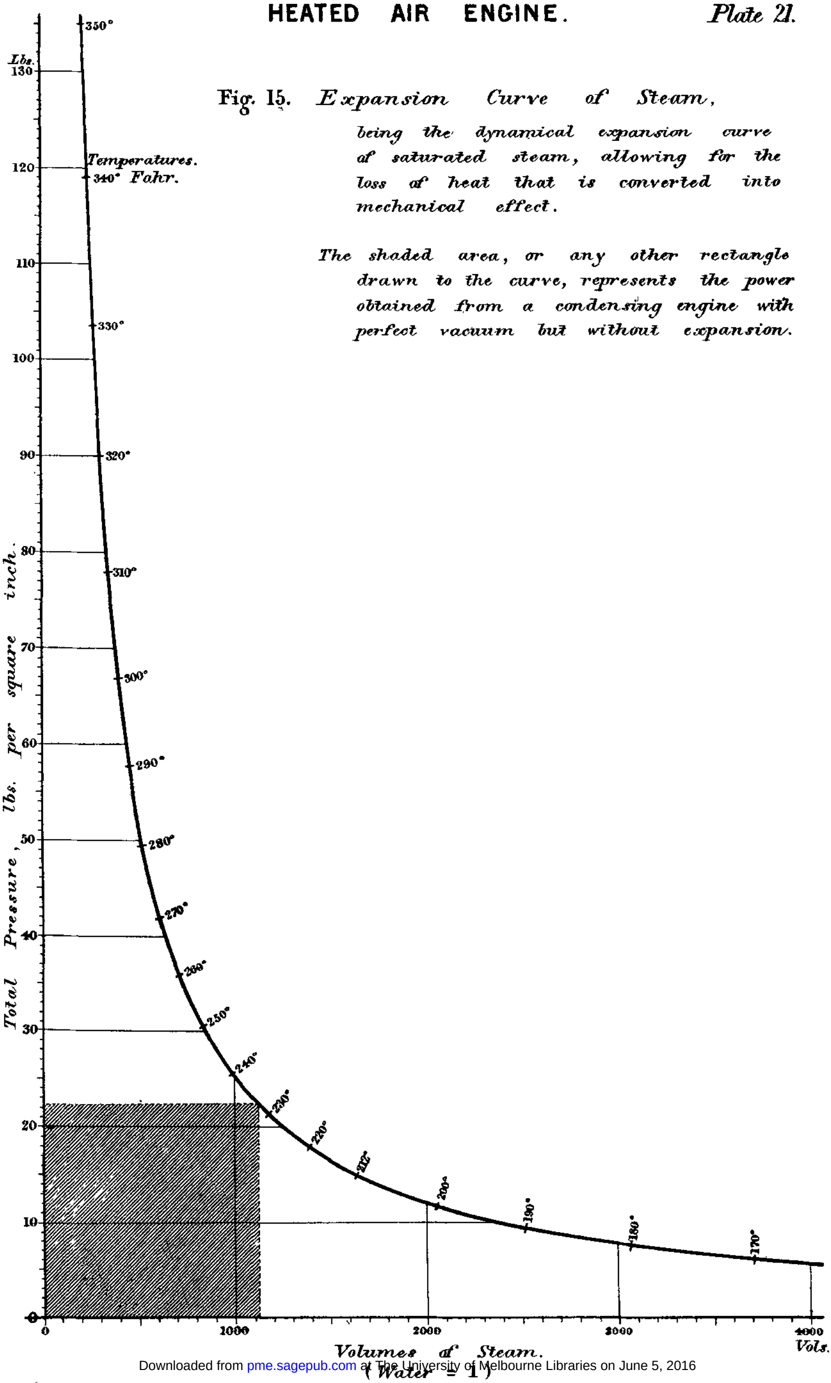


Fig. 15. *Expansion Curve of Steam,*

being the dynamical expansion curve of saturated steam, allowing for the loss of heat that is converted into mechanical effect.

The shaded area, or any other rectangle drawn to the curve, represents the power obtained from a condensing engine with perfect vacuum but without expansion.

(Proceedings Inst. M. E. 1873.)