(*Paper No. 2187.*)

"Experiments on a Direct-acting Steam-Pump."

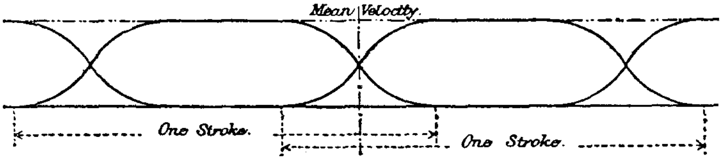
By John George Mair, M. Inst. C.E.

In the Autumn of 1885 the Author casually heard that a system of pumping, invented by Mr. C. C. Worthington, of the firm of Henry R. Worthington, of New York, was in use in the United States, enabling a Worthington direct-acting steam-pump to work with as high a rate of expansion as any type of crank and fly-wheel engine, and at the same time exert a steady and uniform pressure on the pump-plunger. He therefore determined to investigate and test its working. The motions of both a steam-piston and a water-plunger being rectilinear, a connecting-rod, crank and fly-wheel having a rotative motion, are superfluous except for the purposes of expansive working or controlling the length of stroke. Mr. E. D. Leavitt, jun., who has a large and varied practice as a hydraulic engineer in America, explained to the Author generally the peculiarity of the design of the engine, expressed himself in the highest terms of its mechanical efficiency, and kindly offered to assist in any experiments it was proposed to carry out.

The Author took as an assistant, Mr. Henry Smith, Assoc. M. Inst. C.E., and in order that no question should be raised as to the accuracy of the necessary testing instruments, a circular orifice, through which to measure the air-pump discharge, three Kew-tested thermometers, an indicator, and also three tested Bourdon-gauges for water and steam pressures, were sent from England.

The inventor kindly placed an engine and its boiler entirely at the service of the Author, and expressed a wish that the trials should be as complete and exhaustive as it was possible to make them. The engine was at work at Brooklyn, New York, and was put up solely for experimental purposes. It pumped out of a well, and through weighted relief-valves back to the well, so that trials could be made which would have been impossible had the engine been performing the ordinary duty at a waterworks. To pump about 1,700 gallons a minute through weighted and spring-valves is a more difficult service than pumping against a head of water in a main. It was, therefore, evident that whatever results were obtained on the trials, they could be readily repeated and improved upon in practice. Nearly twenty-five years have passed since the first Worthington compound-condensing engine was erected and set to work in America; since then great improvements have been made, and now these machines pump 40 per cent. of the total water-supply of the United States. The system, however, is not much known in England, and so little attention has it attracted, that there are no records of it in the Proceedings of this Institution, or in those of the Institution of Mechanical Engineers. In fact, it has not even been alluded to by the Authors of the various papers on pumping-engines that have been published from time to time. Practically the system consists of two independent engines and pumps lying side by side, the motion of one engine actuating the valves of the other. The delivery of water from the pumps is almost absolutely uniform, and although an air vessel is usually placed on the discharge chamber, it is generally water-logged, and the Author could not tell the difference in working either with or without air.

FIG. 1.



FLOW FROM WORTHINGTON PUMP.

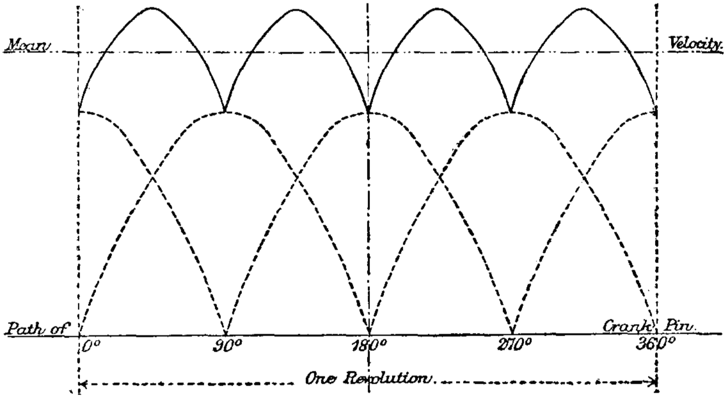
Fig. 1 represents, approximately, the flow from a Worthington pump at each point of the stroke. As soon as one pump begins to slow down at the end of the stroke the other pump starts, so that by combining the flow it will be seen how uniform it is. With any pump driven by a crank and connecting-rod, and even when two pumps are coupled on one crank-shaft at right-angles, great variation exists in the quantity of water delivered at different parts of the stroke, owing to the varying speed of the pistons, necessitating an air-vessel being placed on the delivery main.

The delivery from a compound rotative engine, with cranks at right-angles, working two double-acting pumps, supposing the connecting-rod to be indefinitely long, is shown by Fig. 2. The deliveries are added together and shown in full lines; the variation of flow in this case is sufficient to make the pressures fluctuate to such an extent that accidents are very liable to occur when working without air. The Author, in his own practice, has met with many cases where accidents have happened to the pump-work and rising mains, when through carelessness no air was in the vessel;

but with the uniform delivery of the type of twin-pumps before described an air-vessel is not needed, and it is this uniform delivery that permits the use of the engine for pumping through the oil-pipe lines where the friction in the mains amounts to 3,450 feet head at normal speed. With the single- or double-acting pumps first used for this service, where the flow ceased at the end of the stroke, the pressure gauge fluctuated hundreds of pounds on the square inch with a corresponding result of broken pipes and pumps.

The oil-pipe lines are of different diameters and lengths, and, taking as an example one that came under the personal notice of the Author, namely, 6 inches in diameter and about 30 miles long, through which two 10-inch double plunger-pumps were forcing oil, the main would contain, if filled with oil at a specific gravity of 0·87, over 750 tons, and as this weight may be considered as attached to the pump-piston, a very simple calculation will show what excessive pressures are set up when such a weight is moved at a variable velocity, and also as the pressure in the pump is nearly all due to friction in the main, which increases or decreases practically as the square of the speed of the flow in it, it can be seen that the only system of pumping capable of working with safety is that in which the delivery from the pump is uniform and regular at every part of the stroke. There are now on the oil lines some sixty or seventy compound condensing engines of various powers up to 600 or 800 HP. The service is a peculiar one, and the difficulties that have been overcome reflect the greatest credit on the engineers of the line.

Fig. 2.



Velocity Diagrams.
Two Double-acting Pumps with Cranks at Right Angles.

The Worthington engine just referred to, although as economical in fuel as an ordinary Cornish engine, and more so if the first cost and the expense of foundations and houses is taken into account, can be beaten in economy of fuel by a well-designed compound rotative-engine working at a high rate of expansion. Mr. C. C. Worthington therefore applied himself to attach to his engine a form of compensation which would absorb or store up the excess of power at the steam end during the first part of the stroke, and give it out again during the last part of the stroke, when owing to expansion the steam-pressure falls below the water-pressure.

Now the main point to be observed in designing such an arrangement, is to obtain a perfectly uniform pressure on the pump plunger, so as to get a steady delivery of water. To effect this, compensators of many varied forms were schemed, and an experimental engine was made that would work up to about 150 HP., and a boiler arranged specially to supply it with steam. As it was almost impossible to obtain from the waterworks sufficient water for the engine, a well was sunk, the entire plant with experiments having cost about £10,000. The engine was worked for about a year and a half continuously, and found to be such a perfect success that several are now at work, and many others are being made on the system that was in practice found best.

If the steam-pressure diagrams of an expansive compound-engine are combined together, it will be found that there is an excess of pressure *a b* at the commencement of the stroke (Plate 8, Figs. 1) over the mean pressure decreasing to half-stroke, and after that point there is an increasing deficiency of pressure *b c*. This variation with a rotative-engine is taken up by the fly-wheel, but in the high-duty Worthington engine there are two small cylinders (by preference oscillating) which are attached to the piston-rod, containing water or air under pressure. Referring to Plate 8, Figs. 2, it will be readily seen that the excess of work *a b*, which is a maximum at the commencement of the stroke and decreases to nothing at half-stroke, is taken up by these small cylinders. Directly after half-stroke, when the steam-pressure is below the water-pressure, they give out work *h k*, which increases to the end of the stroke, so that if the work absorbed or given out in the compensators is combined with the steam diagrams, a perfectly steady pressure-line is obtained, and the engine makes its stroke at a uniform speed, so that a straight pump-diagram is obtained. The diagrams, Plate 8, Figs. 1, were taken from a high-duty pumping engine, working under ordinary service at New Bedford, Mass., U.S.A., the steam being expanded during the time it was taken some 10 or 12 times.

Engine Trials.—These trials were all carried out in a similar manner to those before made by the Author.[1] Plate 8, Figs. 3, give the general arrangement, plan of the boiler, engine, and pump, together with the position and details of the measuring tanks. The engine and pump are shown in Plate 8, Fig. 4. The feed water was measured in a cast-iron pipe, Plate 8, Fig. 5, with an overflow pipe in it, and its contents to the level of the pipe were weighed on tested scales many times over, the temperature being noted each time, so that the quantity of water in the pipe which was used as a feed measuring-tank may be relied on as accurate. From the pipe the water was run into a wooden tank, out of which it was taken by the feed donkey and pumped into the boiler. Mr. C. C. Worthington placed one of his water-meters between the feed-pump and the boiler, and the meter readings agreed within $\frac{1}{4}$ per cent. with the measurements made by the Author.

The boiler was of the Corliss type, vertical, 5 feet 4 inches in diameter by 14 feet high, with vertical tubes; and as the heat went direct from the fire through the tubes, and so heated the steam above the water-level, the steam was slightly superheated. A thermometer was fixed in the steam-pipe in the engine-house, the readings of which are given in the Tables. The steam-pipe went across a yard in the open air, but being well covered with non-conducting composition, and the steam being slightly superheated, condensation to any marked extent was prevented. The steam-jackets drained into a tank, which was carefully measured, and when full the condensed water was discharged into a drain, and the time noted. The working-steam, after leaving the engine, passed through the eduction pipe to an independent air-pump and condenser, worked by a separate engine. Both the feed-donkey and the air-pump engine were supplied with steam from a separate boiler, so that, in taking the efficiency of the engine into account, the work done by these pumps should be deducted. Their having a separate steam-supply did not, of course, affect the heat used by the main engine itself, but only the efficiency, that is, the relation of the indicated HP. to the pump HP. The steam from the main engine, after being condensed and passing through the air-pump, was delivered through a short length of pipe to the discharge-tank (Plate 8, Fig. 6), where it was gauged through a circular orifice 3 inches in diameter. The temperatures of injection and air-pump discharge were read, and the head measured every quarter of an hour.

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[1] Minutes of Proceedings Inst. C.E. vols. lxx. and lxxix.

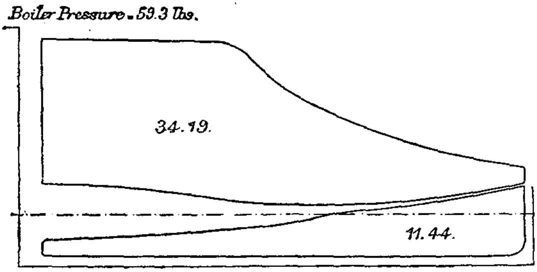
Eight new indicators, made by the American Steam-Gauge Co. (and which were checked with the English one) were on the steam-cylinders fixed close up to each head, and the diagrams were averaged by ordinates in New York, and checked by planimeters in England. Two counters were on the engine, which checked each other, and two tested water-pressure gauges were fixed on the delivery-main.

Five assistants were in the engine-room, and four in the boiler-house. A ship's chronometer was used for the time, and every quarter of an hour throughout all the tests gongs were sounded, one in the engine-room and one in the boiler-house, so that all observations were taken at the same instant, and the Author took personal observations all round every half-hour, so that no error could have crept in. Such detailed care was, however, not necessary, as the rejected heat was measured, and that gives the best check on the boiler-supply. The stroke was kept the full length, touching the cylinder-heads each time; and so regularly did the engine run that, for each trial, all observations were almost exact counterparts of each other. Independently of measuring the heat-supply, many interesting experiments were made; the engine was slowed down until it made one double stroke in a minute and a half. The pump had its pressure suddenly released, to show the safety of the engine, and the air-vessel was filled with air, and was also water-logged; the compensators were put out of gear; in fact, every experiment was tried that was of value. The Author made nine full trials, and Mr. Smith made three more after the Author had left New York. These trials were so regular that it is sufficient to give the details of three.

The absolute quantity of water delivered by the pumps could not be exactly ascertained; but even if the full displacement of the plunger was not made, it would not affect the results of the trials, as the pump HP. was taken from the actual pressure in the delivery main (as recorded by the gauges tested in England) against the area of the plunger, all connections and by-passes being carefully shut off and plugged before the trials. At the end of each stroke a pause is made, which allows the pump-valves to close before the return-stroke, and so prevents slip through them.

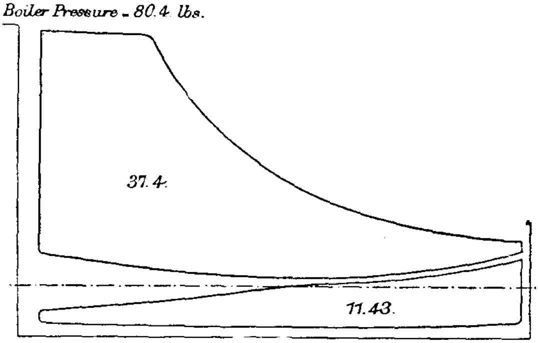
The average efficiency on the three trials is 91·5 per cent., but, from this has to be deducted the power it would require to work the air- and feed-pumps, and taking this at 3½ per cent. would give a net result of 88 per cent. efficiency, or a higher value than is generally obtained by a crank and fly-wheel engine when the pump-valves are tight. This is what would be expected, as the

FIG. 3.



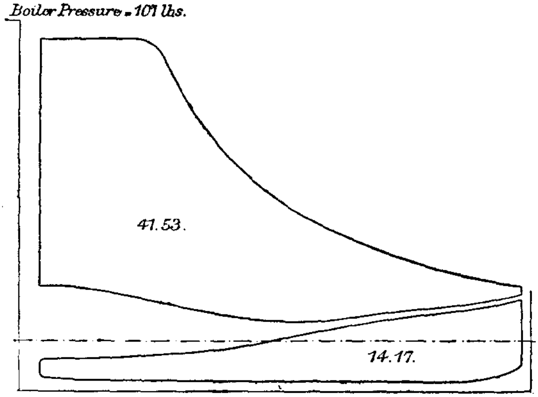
Scale $\frac{1}{60}$.

FIG. 4.



Scale $\frac{1}{60}$.

FIG. 5.



Scale $\frac{1}{60}$.

pistons of the compensating cylinders and trunnions certainly pro duce less friction than the crank-shaft bearings, crank and cross-head pins, guide-bars, eccentric straps, &c., of a fly-wheel engine.

The piston-speed, as compared with the English practice, is very low, and naturally the repairs and renewals with these engines are of a most trivial character, even over long and extended periods of working. The foundations are simple, as the stresses are self-contained; in fact, the engine experimented with by the Author was hardly on any foundation, and when doing 165 indicated HP., as it did on one of the trials, it was perfectly steady, and worked without noise or vibration.

The following is a summary of three trials:—No. 1 on December 24th, No. 2 on December 19th, and No. 3 on December 22nd, 1885 (Figs. 3, 4, 5).

No. of trial	1	2	3
Double strokes per minute	45·0	39·26	40·10
Boiler-pressure . . . . lbs.	59·3	80·4	101·0
Feed-water per minute (tank measurement) (Plate 8, Fig. 5) . . . . lbs.	34·12	30·33	36·26
Jacket drains per minute . . . . . ,,	4·22	4·15	4·57
Temperature of steam	359°	376°	390°
Pressure on pump, including suction lbs.	78·5	80·5	97·0
,, in compensators . . . . . ,,	162·5	195·0	250·5
Mean pressure in high-pressure cylinder ,,	34·19	37·40	41·53
,, in low-pressure cylinder ,,	11·44	11·43	14·17
Temperature of injection	57·18°	57·10°	57·30°
,, air-pump discharge . . .	84·95°	81·06°	89·50°
Head over centres of orifice . . . . . ft.	1·727	1·802	1·397
Air-pump discharge per minute . . lbs.	1,174·0	1,197·0	1,056·0
Injection water . . . . ,,	1,144·0	1,171·0	1,024·0

Heat passing through Engine per minute—			
T U from boiler, saturated steam through cylinders	35,132·0	30,919·0	37,553·0
,, ,, superheat in steam . .	853·0	772·0	906·0
,, ,, condensation in jackets .	3,794·0	3,677·0	4,003·0
Total . .	39,779·0	35,368·0	42,462·0
Heat retained in condensed steam. . .	1,585·0	1,283·0	1,822·0
,, absorbed by injection-water . . .	31,769·0	28,057·0	32,972·0
,, ,, indicated work . . .	5,096·0	4,621·0	5,579·0
,, ,, radiation	440·0	440·0	440·0
Error	889·0	967·0	1,649·0
Total. .	39,779·0	35,368·0	42,462·0
Percentage of error to total heat passing through engine per minute	2·2	2·7	3·8

Indicated HP.	119·2	108·1	130·5
Pump HP.	109·3	97·9	120·4
Efficiency per cent.	91·7	90·6	92·3
Feed per I.HP. per hour through cylinders	15·05	14·53	14·57
„ „ „ jackets	2·12	2·30	2·10
Piston speed per minute per engine . . ft.	97·5	85·0	86·9
Boiler-pressure . . . . lbs.	59·3	80·4	101·0
Number of expansions	9·2	13·2	14·1
T U per I.HP. per minute	334·0	327·0	325·0
Donkin's coefficient	273·5	265·2	260·6

T U per I.HP. per minute calculated from the temperature of the air-pump discharge	320·0	315·0	311·0
Lbs. of coal per I.HP. per hour, supposing feed taken from hot well and the coal to give up 11,000 T U per lb.[1]	1·74	1·72	1·70
Duty in 1,000,000 foot-lbs. of water raised per 112 lbs. of coal taking 88 per cent. efficiency	112·1	113·4	114·8
Disposal of Heat used—			
As indicated work . . . . per cent.	13·3	13·5	13·7
Rejected heat and error . . . . . „	85·5	85·2	85·2
Radiation . . . . „	1·2	1·3	1·1

In order to ascertain exactly the dimensions of the engine and pump under test, the cylinder and pump-covers were taken off, and gauges made of the diameters of the four cylinders and their piston-rods, and of the two pump-plungers and their rods; these gauges were brought to London and measured with a standard Whitworth rule, the mean areas and lengths being as follow:—

Low-pressure cylinders, area	1,013·0 sq. ins.
High „ „ „	251·0 „
Pump plungers „	235·75 „
Stroke, length	26·00 ins.
Clearance in low-pressure cylinder	596·0 cub. ins.
„ high „ „	336·0 „

As before stated, the coal was not weighed; and in the Table above 11,000 T U is taken, so that these trials can be compared with those previously made by the Author.[2]

The engine worked perfectly on all the trials; was easily handled, and fully justified the opinion of its merits expressed by Mr. E. D. Leavitt, jun., and the inventor is to be congratulated on having achieved a result which could only have been arrived

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[1] Minutes of Proceedings Inst. C.E. vol. lxx. p. 336.

[2] *Ibid.* vols. lxx. and lxxix.

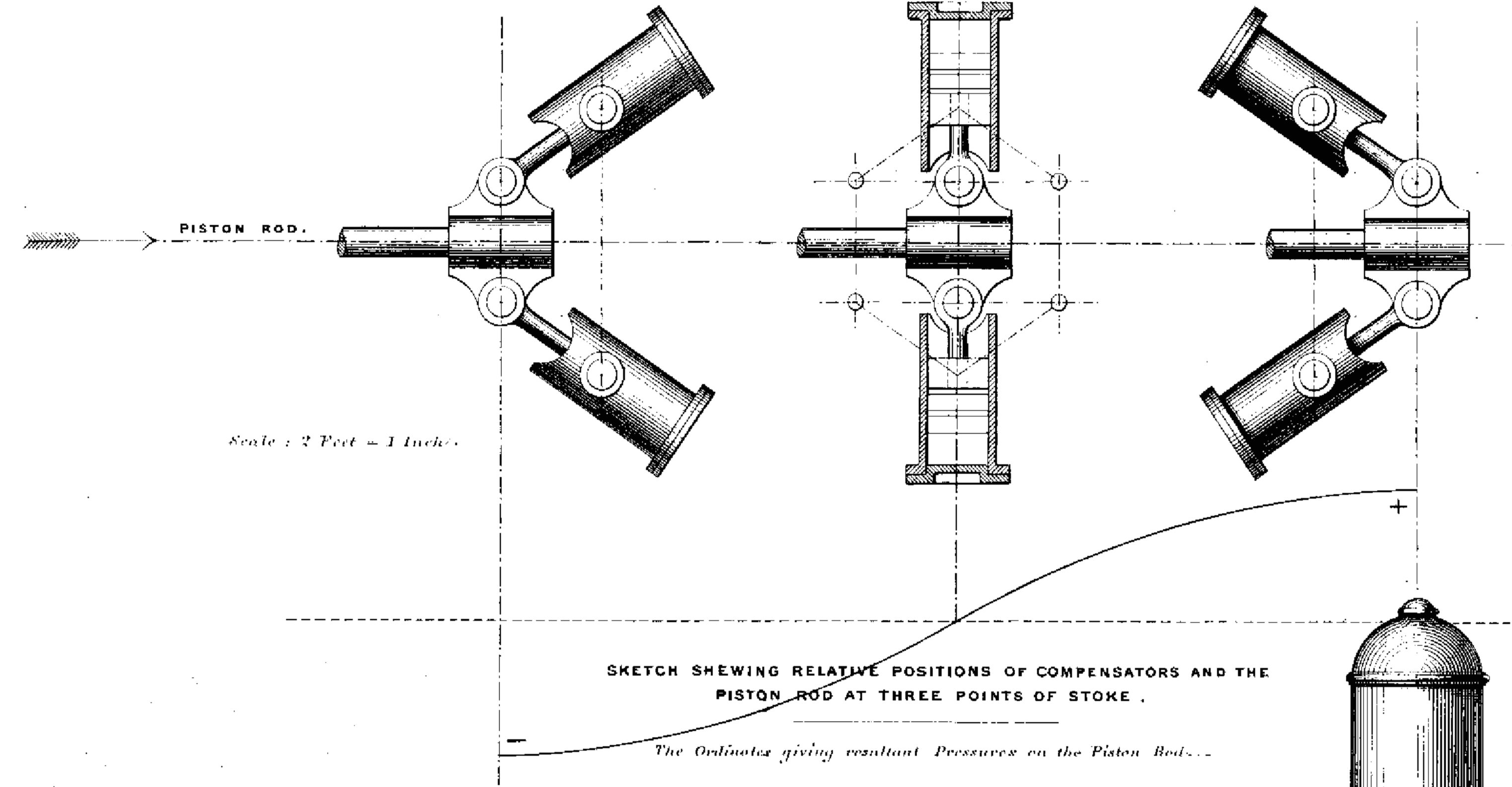
at by a thorough knowledge of mechanics, coupled with great perseverance and enterprise.

In conclusion, the Author begs to tender his best thanks to Mr. C. C. Worthington; to his partner Mr. W. A. Perry, and also to Mr. Barr, Mr. Root, and other members of the staff, for their kind assistance, and for the careful manner in which they carried out the instructions of the Author relative to preparing the engine for testing.

The Paper is accompanied by several diagrams, from which Plate 8, and the Figs. in the text have been prepared.

EXPERIMENTS ON A DIRECT-ACTING STEAM PUMP.

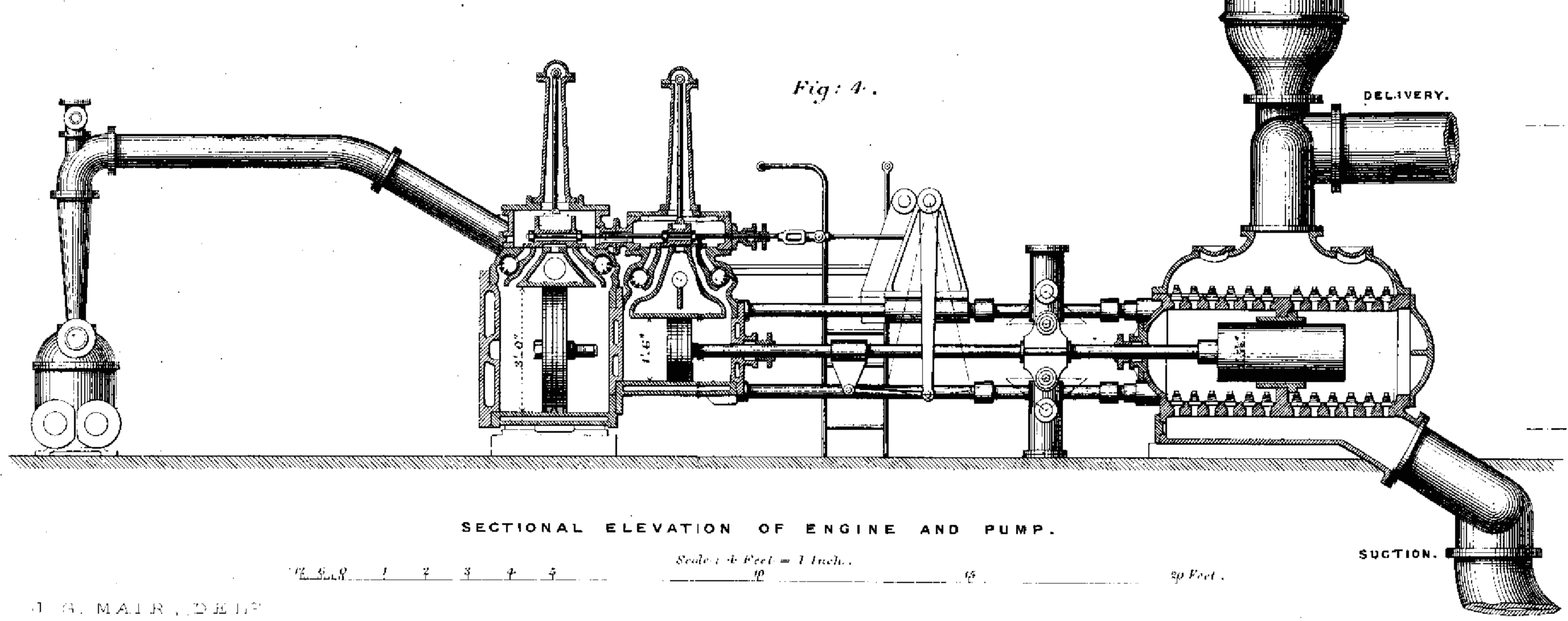
Figs: 2.



SKETCH SHEWING RELATIVE POSITIONS OF COMPENSATORS AND THE PISTON ROD AT THREE POINTS OF STOKE.

The Ordinates giving resultant Pressures on the Piston Rod.

Fig: 4.



SECTIONAL ELEVATION OF ENGINE AND PUMP.

Scale: 4 Feet = 1 Inch.

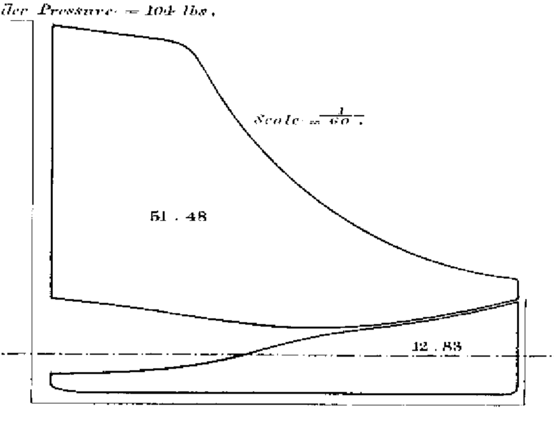
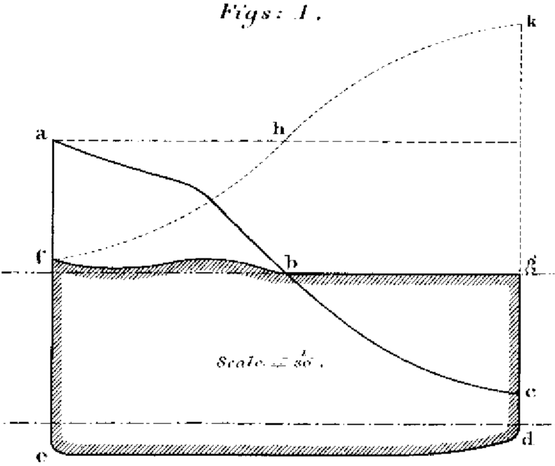


DIAGRAM FROM ENGINE. NEW BEDFORD W. W.

Figs: 1.



COMBINED DIAGRAM. NEW BEDFORD W. W.

a b c d e a. *shews Combined Diagram of H. P. and L. P. Cylinder* ....
f h k, *shews resultant Pressures from Compensators.* ——
f b g d e f, *Diagram of effective Pressures on Piston Rod.* ——

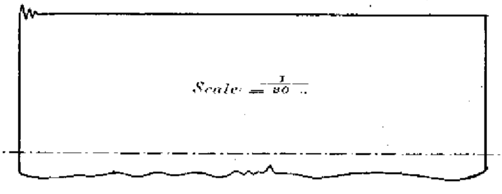
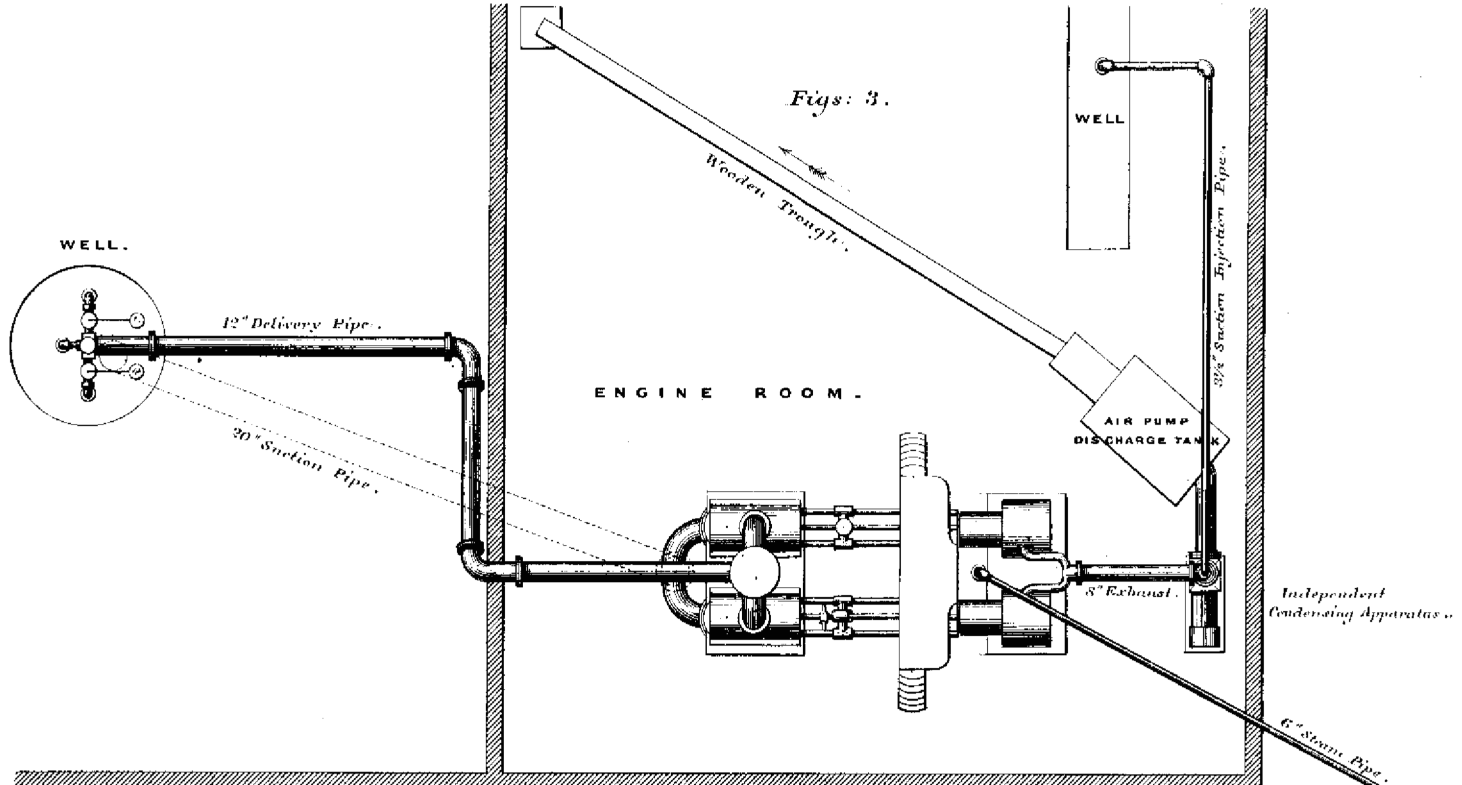
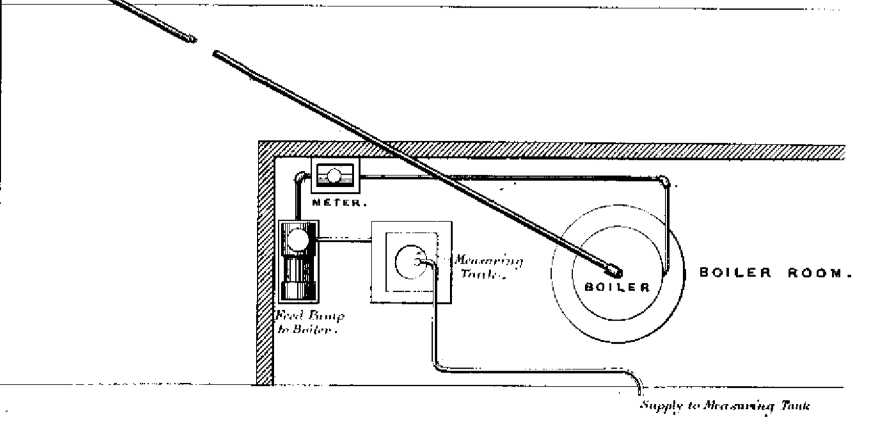


DIAGRAM FROM PUMP. NEW BEDFORD W. W.

Figs: 3.

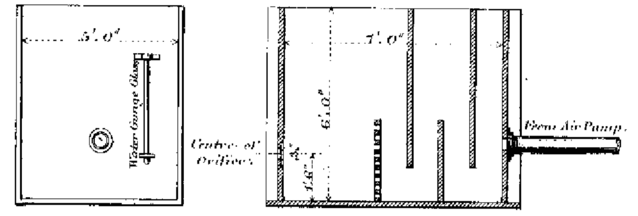




PLAN SHEWING ARRANGEMENTS FOR TESTING THE ENGINE.

Scale 12 Feet = 1 Inch.

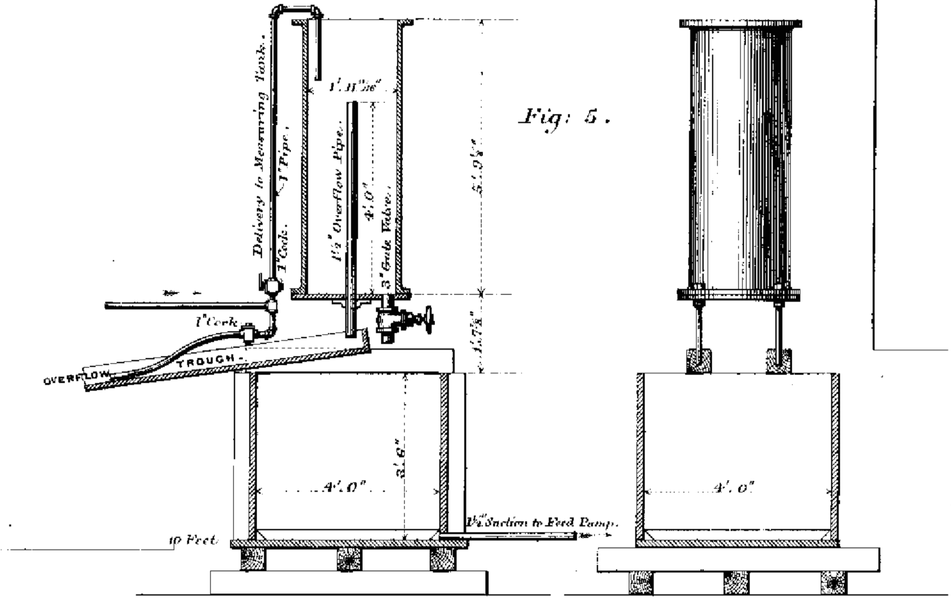
Fig: 6.



AIR PUMP DELIVERY TANK.

Scale: 6 Feet = 1 Inch.

Fig: 5.



Scale: 4 Feet = 1 Inch.

FEED WATER MEASURING APPARATUS.

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THOS. KELL & SON, LITH. 40, KING ST. COVENT GARDEN