CHAPTER III.

THE DEVELOPMENT OF THE MODERN STEAM-ENGINE. JAMES WATT AND HIS CONTEMPORARIES.

THE world is now entering upon the Mechanical Epoch. There is nothing in the future more sure than the great triumphs which that epoch is to achieve. It has already advanced to some glorious conquests. What miracles of invention now crowd upon us! Look abroad, and contemplate the infinite achievements of the steam-power.

And yet we have only begun—we are but on the threshold of this epoch. . . . What is it but the setting of the great distinctive seal upon the nineteenth century?—an advertisement of the fact that society has risen to occupy a higher platform than ever before?—a proclamation from the high places, announcing honor, honor immortal, to the workmen who fill this world with beauty, comfort, and power—honor to be forever embalmed in history, to be perpetuated in monuments, to be written in the hearts of this and succeeding generations!—KENNEDY.

SECTION I.—JAMES WATT AND HIS INVENTIONS.

THE success of the Newcomen engine naturally attracted the attention of mechanics, and of scientific men as well, to the possibility of making other applications of steam-power.

The best men of the time gave much attention to the subject, but, until James Watt began the work that has made him famous, nothing more was done than to improve the proportions and slightly alter the details of the Newcomen and Calley engine, even by such skillful engineers as Brindley and Smeaton. Of the personal history of the earlier inventors and improvers of the steam-engine, very little is ascertained; but that of Watt has become well known.

James Watt was of an humble lineage, and was born at Greenock, then a little Scotch fishing village, but now a considerable and a busy town, which annually launches

James Watt.

upon the waters of the Clyde a fleet of steamships whose engines are probably, in the aggregate, far more powerful than were all the engines in the world at the date of Watt's birth, January 19, 1736. His grandfather, Thomas Watt, of Crawfordsdyke, near Greenock, was a well-known mathematician about the year 1700, and was for many years a schoolmaster at that place. His father was a prominent citizen of Greenock, and was at various times chief magistrate and treasurer of the town. James Watt was a bright boy, but exceedingly delicate in health, and quite unable to attend school regularly, or to apply himself closely to either study or play. His early education was given by his parents, who were respectable and intelligent people, and the tools borrowed from his father's carpenter-bench served at once to amuse him and to give him a dexterity and familiarity with their use that must undoubtedly have been of inestimable value to him in after-life.

M. Arago, the eminent French philosopher, who wrote one of the earliest and most interesting biographies of Watt, relates anecdotes of him which, if correct, illustrate well his thoughtfulness and his intelligence, as well as the mechanical bent of the boy's mind. He is said, at the age of six years, to have occupied himself during leisure hours with the solution of geometrical problems; and Arago discovers, in a story in which he is described as experimenting with the tea-kettle,[1] his earliest investigations of the nature and properties of steam.

When finally sent to the village school, his ill health prevented his making rapid progress; and it was only when thirteen or fourteen years of age that he began to show that he was capable of taking the lead in his class, and to exhibit his ability in the study, particularly, of mathematics. His spare time was principally spent in sketching with his pencil, in carving, and in working at the bench, both in wood and metal. He made many ingenious pieces of mechanism, and some beautiful models. His favorite work seemed to be the repairing of nautical instruments. Among other pieces of apparatus made by the boy was a very fine barrel-organ. In boyhood, as in after-life, he was a diligent reader, and seemed to find something to interest him in every book that came into his hands.

At the age of eighteen, Watt was sent to Glasgow, there to reside with his mother's relatives, and to learn the trade of a mathematical-instrument maker. The mechanic with whom he was placed was soon found too indolent, or was otherwise incapable of giving much aid in the project, and Dr. Dick, of the University of Glasgow, with whom Watt became acquainted, advised him to go to London. Accord-

[1] The same story is told of Savery and of Worcester.

ingly, he set out in June, 1755, for the metropolis, where, on his arrival, he arranged with Mr. John Morgan, in Cornhill, to work a year at his chosen business, receiving as compensation 20 guineas. At the end of the year he was compelled, by serious ill-health, to return home.

Having become restored to health, he went again to Glasgow in 1756, with the intention of pursuing his calling there. But, not being the son of a burgess, and not having served his apprenticeship in the town, he was forbidden by the guilds, or trades-unions, to open a shop in Glasgow. Dr. Dick came to his aid, and employed him to repair some apparatus which had been bequeathed to the college. He was finally allowed the use of three rooms in the University building, its authorities not being under the municipal rule. He remained here until 1760, when, the trades no longer objecting, he took a shop in the city; and in 1761 moved again, into a shop on the north side of the Trongate, where he earned a scanty living without molestation, and still kept up his connection with the college. He did some work as a civil engineer in the neighborhood of Glasgow, but soon gave up all other employment, and devoted himself entirely to mechanics.

He spent much of his leisure time—of which he had, at first, more than was desirable—in making philosophical experiments and in the manufacture of musical instruments, in making himself familiar with the sciences, and in devising improvements in the construction of organs. In order to pursue his researches more satisfactorily, he studied German and Italian, and read Smith's "Harmonics," that he might become familiar with the principles of construction of musical instruments. His reading was still very desultory; but the introduction of the Newcomen engine in the neighborhood of Glasgow, and the presence of a model in the college collections, which was placed in his hands, in 1763, for repair, led him to study the history of the steam-engine, and to conduct for himself an experimental research into the properties of steam, with a set of improvised apparatus.

Dr. Robison, then a student of the University, who found Watt's shop a pleasant place in which to spend his leisure, and whose tastes affiliated so strongly with those of Watt that they became friends immediately upon making acquaintance, called the attention of the instrument-maker to the steam-engine as early as 1759, and suggested that it might be applied to the propulsion of carriages. Watt was at once interested, and went to work on a little model, having tin steam-cylinders and pistons connected to the driving-wheels by an intermediate system of gearing. The scheme was afterwards given up, and was not revived by Watt for a quarter of a century.

Watt studied chemistry, and was assisted by the advice and instruction of Dr. Black, who was then making the researches which resulted in the discovery of "latent heat." His proposal to repair the model Newcomen engine in the college collections led to his study of Desagulier's treatise, and of the works of Switzer and others. He thus learned what bad been done by Savery and by Newcomen, and by those who had improved the engine of the latter.

In his own experiments he used, at first, apothecaries' phials and hollow canes for steam reservoirs and pipes, and later a Papin's digester and a common syringe. The latter combination made a non-condensing engine, in which he used steam at a pressure of 15 pounds per square inch. The valve was worked by hand, and Watt saw that an automatic valve-gear only was needed to make a working machine. This experiment, however, led to no practical result. He finally took hold of the Newcomen model, which had been obtained from London, where it had been sent for repairs, and, putting it in good working order, commenced experiments with that in 1764.

The Newcomen model, as it happened, had a boiler which, although made to a scale from engines in actual use, was quite incapable of furnishing steam enough to work the engine. It was about nine inches in diameter; the steam-cylinder was two inches in diameter, and of six inches stroke of piston, arranged as in Fig. 24, which is a picture of the model as it now appears. It is retained among the most carefully-preserved treasures of the University of Glasgow.

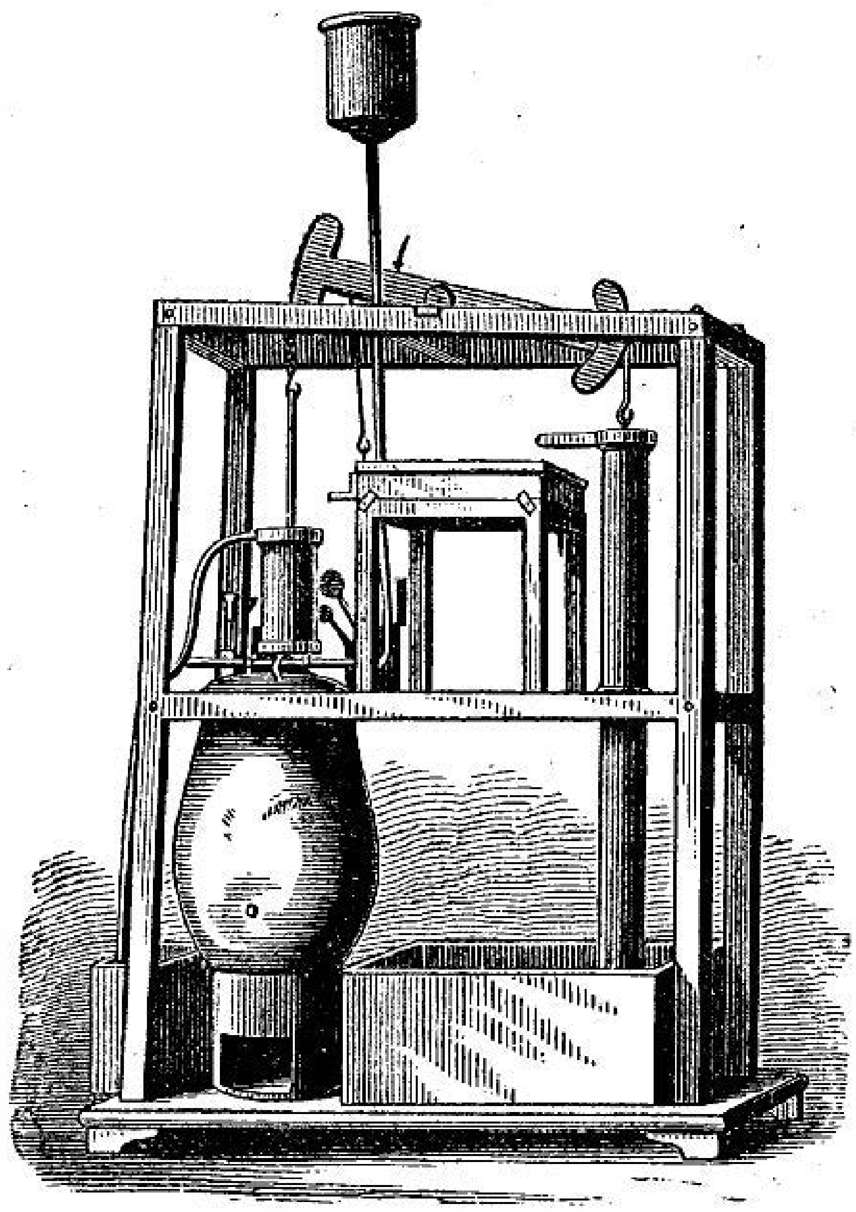


FIG. 24.—The Newcomen Model.

Watt made a new boiler for the experimental investigation on which he was about to enter, and arranged it in such a manner that he could measure the quantity of water evaporated and of steam used at every stroke of the engine.

He soon discovered that it required but a very small quantity of steam to heat a very large quantity of water, and immediately attempted to determine with precision the relative weights of steam and water in the steam-cylinder when condensation took place at the down-stroke of the engine, and thus independently proved the existence of that "latent heat," the discovery of which constitutes, also, one of the greatest of Dr. Black's claims to distinction. Watt at once went to Dr. Black and related the remarkable fact which he had thus detected, and was, in turn, taught by Black the character of the phenomenon as it had been explained to his classes by the latter some little time previously. Watt found that, at the boiling-point, his steam, condensing, was capable of heating six times its weight of water such as was used for producing condensation.

Perceiving that steam, weight for weight even, was a vastly greater absorbent and reservoir of heat than water, Watt saw plainly the importance of taking greater care to economize it than had previously been customary. He first attempted to economize in the boiler, and made boilers with wooden "shells," in order to prevent losses by conduction and radiation, and used a larger number of flues to secure more complete absorption of the heat from the furnace-gases. He also covered his steam-pipes with non-conducting materials, and took every precaution that his ingenuity could devise to secure complete utilization of the heat of combustion. He soon found, however, that he was not working at the most important point, and that the great source of loss was to be found in defects which he noted in the action of the steam in the cylinder. He soon concluded that the sources of loss of heat in the Newcomen engine—which would be greatly exaggerated in a small model—were:

First, the dissipation of heat by the cylinder itself, which was of brass, and was both a good conductor and a good radiator.

Secondly, the loss of heat consequent upon the necessity of cooling down the cylinder at every stroke, in producing the vacuum.

Thirdly, the loss of power due to the pressure of vapor beneath the piston, which was a consequence of the imperfect method of condensation.

He first made a cylinder of non-conducting material—wood soaked in oil and then baked—and obtained a decided advantage in economy of steam. He then conducted a series of very accurate experiments upon the temperature and pressure of steam at such points on the scale as he could readily reach, and, constructing a curve with his results, the abscesses representing temperatures and the pressures being represented by the ordinates, he ran the curve backward until he had obtained closely-approximate measures of temperatures less than 212°, and pressures less than atmospheric. He thus found that, with the amount of injection-water used in the Newcomen engine, bringing the temperature of the interior, as he found, down to from 140° to 175° Fahr., a very considerable back-pressure would be met with.

Continuing his examination still further, he measured the amount of steam used at each stroke, and, comparing it with the quantity that would just fill the cylinder, he found that at least *three-fourths was wasted.* The quantity of cold water necessary to produce the condensation of a given weight of steam was next determined; and he found that one pound of steam contained enough heat to raise about six pounds of cold water, as used for condensation, from the temperature of 52° to the boiling-point; and, going still further, he found that he was compelled to use, at each stroke of the Newcomen engine, *four times as much injection-water as should suffice to condense a cylinder full of steam.* This confirmed his previous conclusion that three-fourths of the heat supplied to the engine was wasted.

Watt had now, therefore, determined by his own researches, as he himself enumerates them,[1] the following facts:

"1. The capacities for heat of iron, copper, and of some sorts of wood, as compared with water.

"2. The bulk of steam compared with that of water.

[1] Robison's "Mechanical Philosophy," edited by Brewster.

"3. The quantity of water evaporated in a certain boiler by a pound of coal.

"4. The elasticities of steam at various temperatures greater than that of boiling water, and an approximation to the law which it follows at other temperatures.

"5. How much water in the form of steam was required every stroke by a small Newcomen engine, with a wooden cylinder 6 inches in diameter and 12 inches stroke.

"6. The quantity of cold water required in every stroke to condense the steam in that cylinder, so as to give it a working-power of about 7 pounds on the square inch."

After these well-devised and truly scientific investigations, Watt was enabled to enter upon his work of improving the steam-engine with an intelligent understanding of its existing defects, and with a knowledge of their cause. Watt soon saw that, in order to reduce the losses in the working of the steam in the steam-cylinder, it would be necessary to find some means, as he said, to keep the cylinder "always as hot as the steam that entered it," notwithstanding the great fluctuations of temperature and pressure of the steam during the up and the down strokes. He has told us how, finally, the happy thought occurred to him which relieved him of all difficulty, and led to the series of modifications which at last gave to the world the modern type of steam-engine.

He says:[1] "I had gone to take a walk on a fine Sabbath afternoon. I had entered the Green by the gate at the foot of Charlotte street, and had passed the old washing-house. I was thinking upon the engine at the time, and had gone as far as the herd's house, when the idea came into my mind that, as steam was an elastic body, it would rush into a vacuum, and, if a communication were made between the cylinder and an exhausted vessel, it would rush into it, and might be there condensed without cooling the

[1] "Reminiscences of James Watt," Robert Hart; "Transactions of the Glasgow Archæological Society," 1859.

cylinder. I then saw that I must get rid of the condensed steam and injection-water if I used a jet, as in Newcomen's engine. Two ways of doing this occurred to me: First, the water might be run off by a descending pipe, if an offlet could be got at the depth of 35 or 36 feet, and any air might be extracted by a small pump. The second was, to make the pump large enough to extract both water and air." "I had not walked farther than the Golf-house, when the whole thing was arranged in my mind."

Referring to this invention, Watt said to Prof. Jardine:[1] "When analyzed, the invention would not appear so great as it seemed to be. In the state in which I found the steam-engine, it was no great effort of mind to observe that the quantity of fuel necessary to make it work would forever prevent its extensive utility. The next step in my progress was equally easy—to inquire what was the cause of the great consumption of fuel. This, too, was readily suggested, viz., the waste of fuel which was necessary to bring the whole cylinder, piston, and adjacent parts from the coldness of water to the heat of steam, no fewer than from 15 to 20 times in a minute." It was by pursuing this train of thought that he was led to devise the separate condenser.e

On Monday morning Watt proceeded to make an experimental test of his new invention, using for his steam-cylinder and piston a large brass surgeon's-syringe, 1¾-inch diameter and 10 inches long. At each end was a pipe leading steam from the boiler, and fitted with a cock to act as a steam-valve. A pipe led also from the top of the cylinder to the condenser, the syringe being inverted and the piston-rod hanging downward for convenience. The condenser was made of two pipes of thin tin plate, 10 or 12 inches long,eand about one-sixth of an inch in diameter, standing vertically, and having a connection at the top

[1] "Lives of Boulton and Watt," Smiles.

with a horizontal pipe of larger size, and fitted with a "snifting-valve." Another vertical pipe, about an inch in diameter, was connected to the condenser, and was fitted with a piston, with a view to using it as an "air-pump." The whole was set in a cistern of cold water. The piston-rod of the little steam-cylinder was drilled from end to end to permit the water to be removed from the cylinder. This little model (Fig. 25) worked very satisfactorily, and the perfection of the vacuum was such that the machine lifted a weight of 18 pounds hung upon the piston-rod, as in the

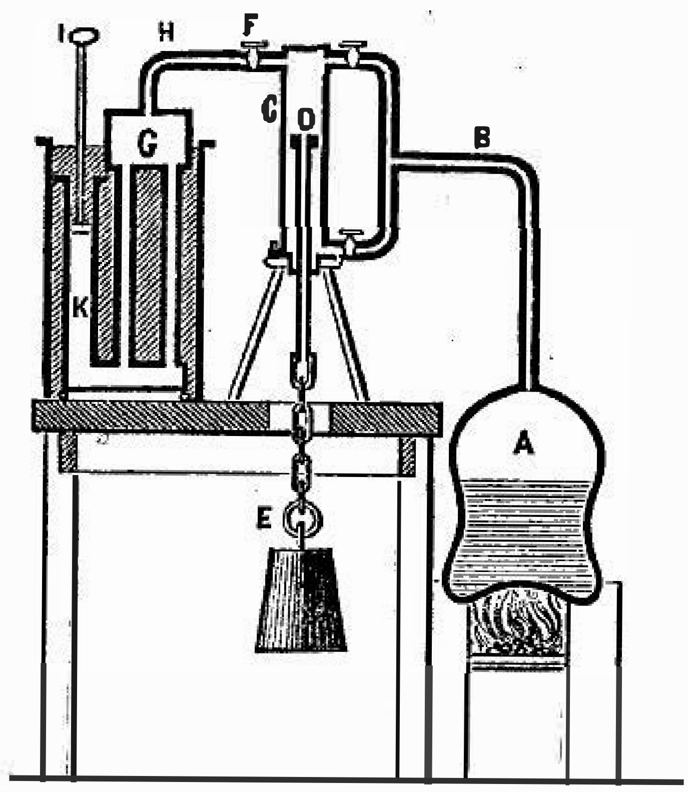


FIG. 25.—Watt's Experiment.

sketch. A larger model was immediately afterward constructed, and the result of its test confirmed fully the anticipations which had been awakened by the first experiment.

Having taken this first step and made such a radical improvement, the success of this invention was no sooner determined than others followed in rapid succession, as consequences of the exigencies arising from the first change in the old Newcomen engine. But in the working out of the forms and proportions of the details of the new engine, even Watt's powerful mind, stored as it was with happily-combined scientific and practical information, was occupied for years. In attaching the separate condenser, he first attempted surface-condensation; but this not succeeding well, he substituted the jet. Some provision became at once necessary for preventing the filling of the condenser with water.

Watt at first intended adopting the expedient which had worked satisfactorily with the less effective condensation of Newcomen's engine—i. e., leading a pipe from the condenser to a depth greater than the height of a column of water which could be counterbalanced by the pressure of the atmosphere; but he subsequently employed the air-pump, which relieves the condenser not only of the water, but of the air which also usually collects in considerable volume in the condenser, and vitiates the vacuum. He next substituted oil and tallow for water in the lubrication of the piston and keeping it steam-tight, in order to avoid the cooling of the cylinder incident to the use of the latter. Another cause of refrigeration of the cylinder, and consequent waste of power in its operation, was seen to be the entrance of the atmosphere, which followed the piston down the cylinder at each stroke, cooling its interior by its contact. This the inventor concluded to prevent by covering the top of the cylinder, allowing the piston-rod to play through a "stuffing-box"—which device had long been known to mechanics.

He accordingly not only covered the top, but surrounded the whole cylinder with an external casing, or "steam-jacket," and allowed the steam from the boiler to pass around the steam-cylinder and to press upon the upper surface of the piston, where its pressure was variable at pleasure, and therefore more manageable than that of the atmosphere. It also, besides keeping the cylinder hot, could do comparatively little harm should it leak by the piston, as it could be condensed, and thus readily disposed of.

When he had concluded to build the larger experimental engine, Watt determined to give his whole time and attention to the work, and hired a room in an old deserted pottery near the Broomielaw. Here he worked with a mechanic—John Gardiner, whom he had taken into his employ—uninterruptedly for many weeks. Meantime, through his friend Dr. Black, probably, he had made the acquaintance of Dr. Roebuck, a wealthy physician, who had, with other Scotch capitalists, just founded the celebrated Carron Iron-Works, and had opened a correspondence with him, in which he kept that gentleman informed of the progress of his work on the new engine.

This engine had a steam-cylinder, Watt tells us, of "five or six" inches diameter, and of two feet stroke. It was of copper, smooth-hammered, but not bored out, and "not very true." This was encased in another cylinder of wood. In August, 1765, he tried the small engine, and wrote Dr. Roebuck that he had had "good success," although the machine was very imperfect. "On turning the exhausting-cock, the piston, when not loaded, ascended as quick as the blow of a hammer, and as quick when loaded with 18 pounds (being 7 pounds on the inch) as it would have done if it had had an injection as usual." He then tells his correspondent that he was about to make the larger model. In October, 1765, he finished the latter. The engine, when ready for trial, was still very imperfect. It nevertheless did good work for so rude a machine.

Watt was now reduced to poverty, and, after borrowing considerable sums from friends, he was finally compelled to give up his scheme for the time, and to seek employment in order to provide for his family. During an interval of about two years he supported himself by surveying, and by the work of exploring coal-fields in the neighborhood of Glasgow for the magistrates of the city. He did not, however, entirely give up his invention.

In 1767, Dr. Roebuck assumed Watt's liabilities to the amount of £1,000, and agreed to provide capital for the prosecution of his experiments and to introduce his invention; and, on the other hand, Watt agreed to surrender to Dr.

Roebuck two-thirds of the patent. Another engine was next built, having a steam-cylinder seven or eight inches in diameter, which was finished in 1768. This worked sufficiently well to induce the partners to ask for a patent, and the specifications and drawings were completed and presented in 1769.

Watt also built and set up several Newcomen engines, partly, perhaps, to make himself thus thoroughly familiar with the practical details of engine-building. Meantime, also, he prepared the plans for, and finally had built, a moderately large engine of his own new type. Its steam-cylinder was 18 inches in diameter, and the stroke of piston was 5 feet. This engine was built at Kinneil, and was finished in September, 1769. It was not all satisfactory in either its construction or its operation. The condenser was a surface-condenser composed of pipes somewhat like that used in his first little model, and did not prove to be satisfactorily tight. The steam-piston leaked seriously, and repeated trials only served to make more evident its imperfections. He was assisted in this time of need by both Dr. Black and Dr. Roebuck; but he felt strongly the risks which he ran of involving his friends in serious losses, and became very despondent. Writing to Dr. Black, he says: "Of all things in life, there is nothing more foolish than inventing;" and probably the majority of inventors have been led to the same opinion by their own experiences.

"Misfortunes never come singly;" and Watt was borne down by the greatest of all misfortunes—the loss of a faithful and affectionate wife—while still unable to see a successful issue of his schemes. Only less disheartening than this was the loss of fortune of his steadfast friend, Dr. Roebuck, and the consequent loss of his aid. It was at about this time, in the year 1769, that negotiations were commenced which resulted in the transfer of the capitalized interest in Watt's engine to the wealthy manufacturer whose name, coupled with that of Watt, afterward became known throughout the civilized world, as the steam-engine in its new form was pushed into use by his energy and business tact.

Watt met Mr. Boulton, who next became his partner, in 1768, on his journey to London to procure his patent, and the latter had then examined Watt's designs, and, at once perceiving their value, proposed to purchase ane interest. Watt was then unable to reply definitely to Boulton's proposition, pending his business arrangements with Dr. Roebuck; but, with Roebuck's consent, afterwards proposed that Boulton should take a one-third interest with himself and partner, paying Roebuck therefor one-half of all expenses previously incurred, and whatever he should choose to add to compensate "for the risk he had run." Subsequently, Dr. Roebuck proposed to transfer to Boulton and to Dr. Small, who was desirous of taking interest with Boulton, one-half of his proprietorship in Watt's inventions, on receiving "a sum not less than one thousand pounds," which should, after the experiments on the engine were completed, be deemed "just and reasonable." Twelve months were allowed for the adjustment of the account. This proposal was accepted in November, 1769.

MATTHEW BOULTON, who now became a partner with James Watt, was the son of a Birmingham silver stamper and piecer, and succeeded to his father's business, building up a great establishment, which, as well as its proprietor, was well known in Watt's time. Watt, writing to Dr. Roebuck before the final arrangement had been made, urged him to close with Boulton for "the following considerationse

"1st. From Mr. Boulton's own character as an ingenious, honest, and rich man. 2dly. From the difficulty and expense there would be of procuring accurate and honest workmen and providing them with proper utensils, and getting a proper overseer or overseers. If, to avoid this inconvenience, you were to contract for the work to be done by a master-workman, you must give up a great share ofe the profit. 3dly. The success of the engine is far from being verified. If Mr. Boulton takes his chance of success from the account I shall write Dr. Small, and pays you any adequate share of the money laid out, it lessens your risk,

Matthew Boulton.

and in a greater proportionethan I think it will lessen your profits. 4thly. The assistance of Mr. Boulton's and Dr. Small's ingenuity (if the latter engage in it) in improving and perfecting the machine may be very considerable, and may enable us to get the better of the difficulties that might otherwise damn it. Lastly, consider my uncertain health, my irresolute and inactive disposition, my inability to bargain and struggle for my own with mankinde: all which disqualify me for any great undertaking. On our side, consider the first outlay and interest, the patent, the present engine, about £200 (though there would not be much loss in making it into a common engine), two years of my time, and the expense of models."

Watt's estimate of the value of Boulton's ingenuity and talent was well-founded. Boulton had shown himself a good scholar, and had acquired considerable knowledge of the languages and of the sciences, particularly of mathematics, after leaving the school from which he graduated into the shop when still a boy. In the shop he soon introduced a number of valuable improvements, and he was always on the lookout for improvements made by others, with a view to their introduction in his business. He was a man of the modern style, and never permitted competitors to excel him in any respect, without the strongest efforts to retain his leading position. He always aimed to earn a reputation for good work, as well as to make money. His father's workshop was at Birmingham; but Boulton, after a time, found that his rapidly-increasing business would compel him to find room for the erection of a more extensive establishment, and he secured land at Soho, two miles distant from Birmingham, and there erected his new manufactory, about 1762.

The business was, at first, the manufacture of ornamental metal-ware, such as metal buttons, buckles, watch-chains, and light filigree and inlaid work. The manufacture of gold and silver plated-ware was soon added, and this branch of business gradually developed into a very extensive manufacture of works of art. Boulton copied fine work wherever he could find it, and often borrowed vases, statuettes, and bronzes of all kinds from the nobility of England, and even from the queen, from which to make copies. The manufacture of inexpensive clocks, such as are now well known throughout the world as an article of American trade, was begun by Boulton. He made some fine astronomical and valuable ornamental clocks, which were better appreciated on the Continent than in England. The business of the Soho manufactory in a few years became so extensive, that its goods were known to every civilized nation, and its growth, under the management of the enterprising, conscientious, and ingenious Boulton, more than kept pace with the accumulation of capital; and the proprietor found himself, by his very prosperity, often driven to the most careful manipulation of his assets, and to making free use of his credit.

Boulton had a remarkable talent for making valuable acquaintances, and for making the most of advantages accruing thereby. In 1758 he made the acquaintance of Benjamin Franklin, who then visited Soho; and in 1766 these distinguished men, who were then unaware of the existence of James Watt, were corresponding, and, in their letters, discussing the applicability of steam-power to various useful purposes. Between the two a new steam-engine was designed, and a model was constructed by Boulton, which was sent to Franklin and exhibited by him in London.

Dr. Darwin seems to have had something to do with this scheme, and the enthusiasm awakened by the promise of success given by this model may have been the origin of the now celebrated prophetic rhymes so often quoted from the works of that eccentric physician and poet. Franklin contributed, as his share in the plan, an idea of so arranging the grate as to prevent the production of smoke. He says: "All that is necessary is to make the smoke of fresh coals pass descending through those that are already ignited." His idea has been, by more recent schemers, repeatedly brought forward as new. Nothing resulted from these experiments of Boulton, Franklin, and Darwin, and the plan of Watt soon superseded all less well-developed plans.

In 1767, Watt visited Soho and carefully inspected Boulton's establishment. He was very favorably impressed by the admirable arrangement of the workshops and the completeness of their outfit, as well as by the perfection of the organization and administration of the business. In the following year he again visited Soho, and this time met

Boulton, who had been absent at the previous visit. The two great mechanics were mutually gratified by the meeting, and each at once acquired for the other the greatest respect and esteem. They discussed Watt's plans, and Boulton then definitely decided not to continue his own experiments, although he had actually commenced the construction of a pumping-engine. With Dr. Small, who was also at Soho, Watt discussed the possibility of applying his engine to the propulsion of carriages, and to other purposes. On his return home, Watt continued his desultory labors on his engines, as already described; and the final completion of the arrangement with Boulton, which immediately followed the failure of Dr. Roebuck, took place some time later.

Before Watt could leave Scotland to join his partner at Soho, it was necessary that he should finish the work which he had in hand, including the surveys of the Caledonian canal, and other smaller works, which he had had in progress some months. He reached Birmingham in the spring of 1774, and was at once domiciled at Soho, where he set at work upon the partly-made engines which had been sent from Scotland some time previously. They had laid, unused and exposed to the weather, at Kinneil three years, and were not in as good order as might have been desired. The *block-tin* steam-cylinder was probably in good condition, but the iron parts were, as Watt said, "perishing," while he had been engaged in his civil engineering work. At leisure moments, during this period, Watt had not entirely neglected his plans for the utilization of steam. He had given much thought, and had expended some time, in experiments upon the plan of using it in a rotary or "wheel" engine. He did not succeed in contriving any plan which seemed to promise success.

It was in November, 1774, that Watt finally announced to his old partner, Dr. Roebuck, the successful trial of the Kinneil engine. He did not write with the usual enthusiasm and extravagance of the inventor, for his frequent disappointments and prolonged suspense had very thoroughly extinguished his vivacity. He simply wrote: "The fire-engine I have invented is now going, and answers much better than any other that has yet been made; and I expect that the invention will be very beneficial to me."

The change of the "atmospheric engine" of Newcomen

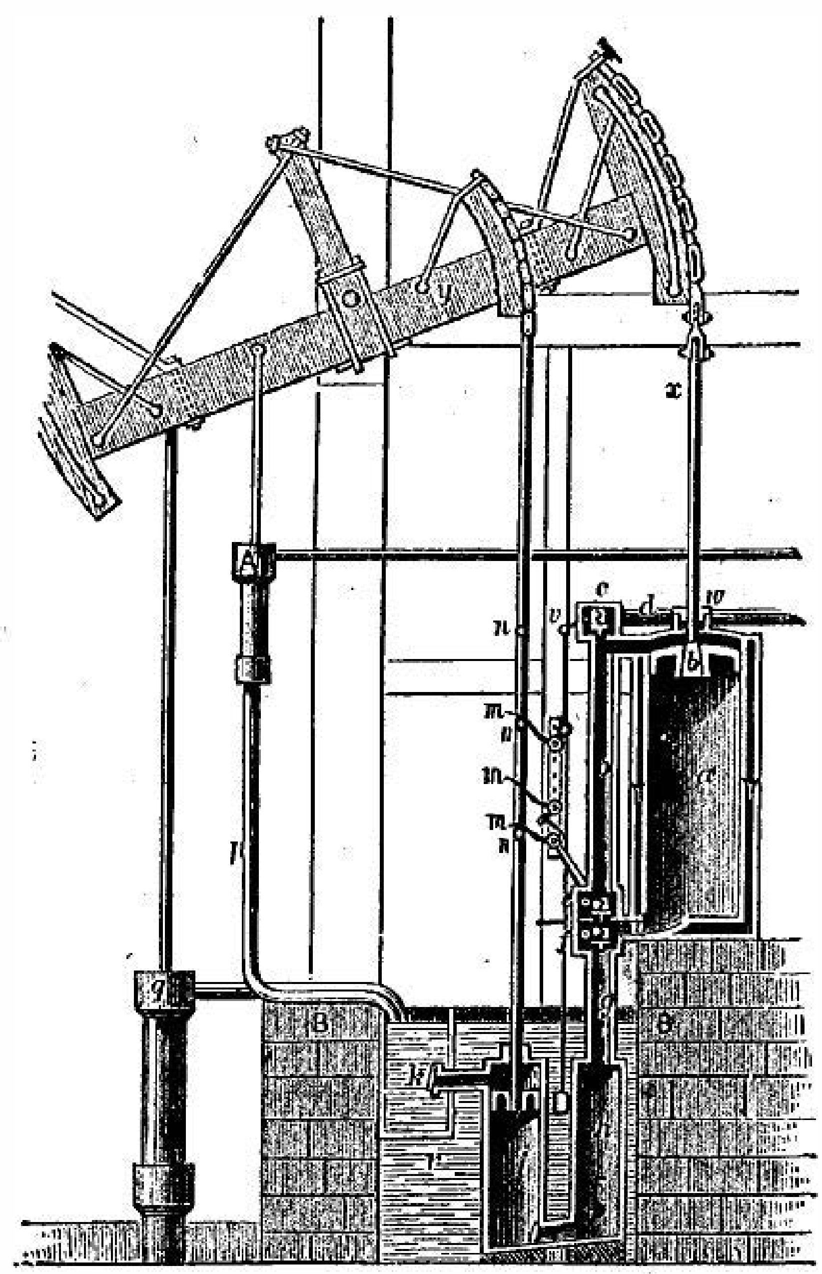


FIG. 26.—Watt's Engine, 1774.

into the modern steam-engine was now completed in its essential details. The first engine which was erected at Kinneil, near Boroughstoness, had a steam-cylinder 18 inches in diameter. It is seen in the accompanying sketch.

In Fig. 26, the steam passes from the boiler through the pipe *d* and the valve *c* to the cylinder-casing or steam-jacket, *Y Y*, and above the piston, *b*, which it follows in its descent in the cylinder, *a*, the valve *f* being at this time open, to allow the exhaust into the condenser, *h*.

The piston now being at the lower end of the cylinder, and the pump-rods at the opposite end of the beam, *y*, being thus raised and the pumps filled with water, the valves *c* and *f* close, while *e* opens, allowing the steam which remains above the piston to flow beneath it, until, the pressures becoming equal above and below, the weight of the pump-rods overbalancing that of the piston, the latter is rapidly drawn to the top of the cylinder, while the steam is displaced above, passing to the under-side of the piston.

The valve *e* is next closed, and *c* and *f* are again opened; the down-stroke is repeated. The water and air entering the condenser are removed at each stroke by the air-pump, *i*, which communicates with the condenser by the passage *s*. The pump *q* supplies condensing-water, and the pump *A* takes away a part of the water of condensation, which is thrown by the air-pump into the "hot-well," *k*, and from it the feed-pump supplies the boiler. The valves are moved by valve-gear very similar to Beighton's and Smeaton's, by the pins, *m m*, in the "plug-frame" or "tappet-rod," *n n*.

The engine is mounted upon a substantial foundation, *B B*. *F* is an opening out of which, before starting the engine, the air is driven from the cylinder and condenser.

The inventions covered by the patent of 1769 were described as follows:

"My method of lessening the consumption of steam, and consequently fuel, in fire-engines, consists in the following principles:

"1st. That the vessel in which the powers of steam are to be employed to work the engine—which is called 'the cylinder' in common fire-engines, and which I call 'the steam-vessel'—must, during the whole time that the engine is at work, be kept as hot as the steam which enters it; first, by inclosing it in a case of wood, or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and thirdly, by suffering neither water nor other substances colder than the steam to enter or touch it during that time.

"2dly. In engines that are to be worked, wholly or partially, by condensation of steam, the steam is to be condensed in vessels distinct from the steam-vessel or cylinder, though occasionally communicating with them. These vessels I call *condensers;* and while the engines are working, these condensers ought at least to be kept as cold as the air in the neighborhood of the engines, by application of water or other cold bodies.

"3dly. Whatever air or other elastic vapor is not condensed by the cold of the condenser, and may impede the working of the engine, is to be drawn out of the steam-vessels or condensers by means of pumps, wrought by the engines themselves, or otherwise.

"4thly. I intend in many cases to employ the expansive force of steam to press on the pistons, or whatever may be used instead of them, in the same manner as the pressure of the atmosphere is now employed in common fire-engines. In cases where cold water cannot be had in plenty, the engines may be wrought by this force of steam only, by discharging the steam into the open air after it has done its office.

"5thly. Where motions round an axis are required, I make the steam-vessels in form of hollow rings or circular channels, with proper inlets and outlets for the steam, mounted on horizontal axles like the wheels of a water-mill. Within them are placed a number of valves that suffer any body to go round the channel in one direction only. In these steam-vessels are placed weights, so fitted to them as to fill up a part or portion of their channels, yet rendered capable of moving freely in them by the means hereinafter mentioned or specified. When the steam is admitted in these engines between these weights and the valves, it acts equally on both, so as to raise the weight on one side of the wheel, and, by the reaction of the valves successively, to give a circular motion to the wheel, the valves opening in the direction in which the weights are pressed, but not in the contrary. As the vessel moves round, it is supplied with steam from the boiler, and that which has performed its office may either be discharged by means of condensers, or into the open air.

"6thly. I intend in some cases to apply a degree of cold not capable of reducing the steam to water, but of contracting it considerably, so that the engines shall be worked by the alternate expansion and contraction of the steam.

"Lastly, instead of using water to render the piston or other parts of the engine air or steam-tight, I employ oils, wax, resinous bodies, fat of animals, quicksilver, and other metals, in their fluid state."

In the construction and erection of his engines, Watt still had great difficulty in finding skillful workmen to make the parts with accuracy, to fit them with care, and to erect them properly when once finished. And the fact that both Newcomen and Watt met with such serious trouble, indicates that, even had the engine been designed earlier, it is quite unlikely that the world would have seenethe steam-engine a success until this time, when mechanics were just acquiring the skill requisite for its construction. But, on the other hand, it is not at all improbable that, had the mechanics of an earlier period been as skillful and as well-educated in the manual niceties of their business, the steam-engine might have been much earlier brought into use.

In the time of the Marquis of Worcester it would have probably been found impossible to obtain workmen to construct the steam-engine of Watt, had it been then invented. Indeed, Watt, upon one occasion, congratulated himself that one of his steam-cylinders only lacked *three-eighths* of an inch of being truly cylindrical.

The history of the steam-engine is from this time a history of the work of the firm of Boulton & Watt. Newcomen engines continued to be built for years after Watt went to Soho, and by many builders. A host of inventors still worked on the most attractive of all mechanical combinations, seeking to effect further improvements. Some inventions were made by contemporaries of Watt, as will be seen hereafter, which were important as being the germs of later growths; but these were nearly all too far in advance of the time, and nearly every successful and important invention which marked the history of steam-power for many years originated in the fertile brain of James Watt.

The defects of the Newcomen engine were so serious, that it was no sooner known that Boulton of Soho had become interested in a new machine for raising water by steam-power, than inquiries came to him from all sides, from mine-owners who were on the point of being drowned out, and from proprietors whose profits were absorbed by the expense of pumping, and who were glad to pay the £5 per horse-power per year finally settled upon as royalty. The London municipal water-works authorities were also ready to negotiate for pumping-engines for raising water to supply the metropolis. The firm was therefore at once driven to make preparations for a large business.

The first and most important matter, however, was to secure an extension of the patent, which was soon to expire. If not renewed, the 15 years of study and toil, of poverty and anxiety, through which Watt had toiled, would prove profitless to the inventor, and the fruits of his genius would have become the unearned property of others.e Watt saw, at one time, little hope of securing the necessary act of Parliament, and was greatly tempted to accept a position tendered him by the Russian Government, upon the solicitation of his old friend, Dr. Robison, then a Professor of Mathematics at the Naval School at Cronstadt. The salary was £1,000—a princely income for a man in Watt's circumstances, and a peculiar temptation to the needy mechanic.

Watt, however, went to London, and, with the help of his own and of Boulton's influential friends, succeeded in getting his bill through. His patent was extended 24 years, and Boulton & Watt set about the work of introducing their engines with the industry and enterprise which characterized their every act.

In the new firm, Boulton took charge of the general business, and Watt superintended the design, construction, and erection of their engines. Boulton's business capacity, with Watt's wonderful mechanical ability—Boulton's physical health, and his vigor and courage, offsetting Watt's feeble health and depression of spirits—and, more than all, Boulton's pecuniary resources, both in his own purse and in those of his friends, enabled the firm to conquer all difficulties, whether in finance, in litigation, or in engineering.

It was only after the successful erection and operation of several engines that Boulton and Watt became legally partners. The understood terms were explicitly stated by Watt toninclude an assignment to Boulton of two-thirds the patent-right; Boulton paying all expenses, advancing stock in trade at an appraised valuation, on which it was to draw interest; Watt making all drawings and designs, and drawing one-third net profits.

As soon as Watt was relieved of the uncertainties regarding his business connections, he married a second wife, who, as Arago says, by "her various talent, soundness of judgment, and strength of character," made a worthy companion to the large-hearted and large-brained engineer. Thenceforward his cares were only such as every business-man expects to be compelled to sustain, and the next ten years were the most prolific in inventions of any period in Watt's life.

From 1775 to 1785 the partners acquired five patents, covering a large number of valuable improvements upon the steam-engine, and several independent inventions. The first of these patents covered the now familiar and universally-used copying-press for letters, and a machine for drying cloth by passing it between copper rollers filled with steam of sufficiently high temperature to rapidly evaporate the moisture. This patent was issued February 14, 1780.

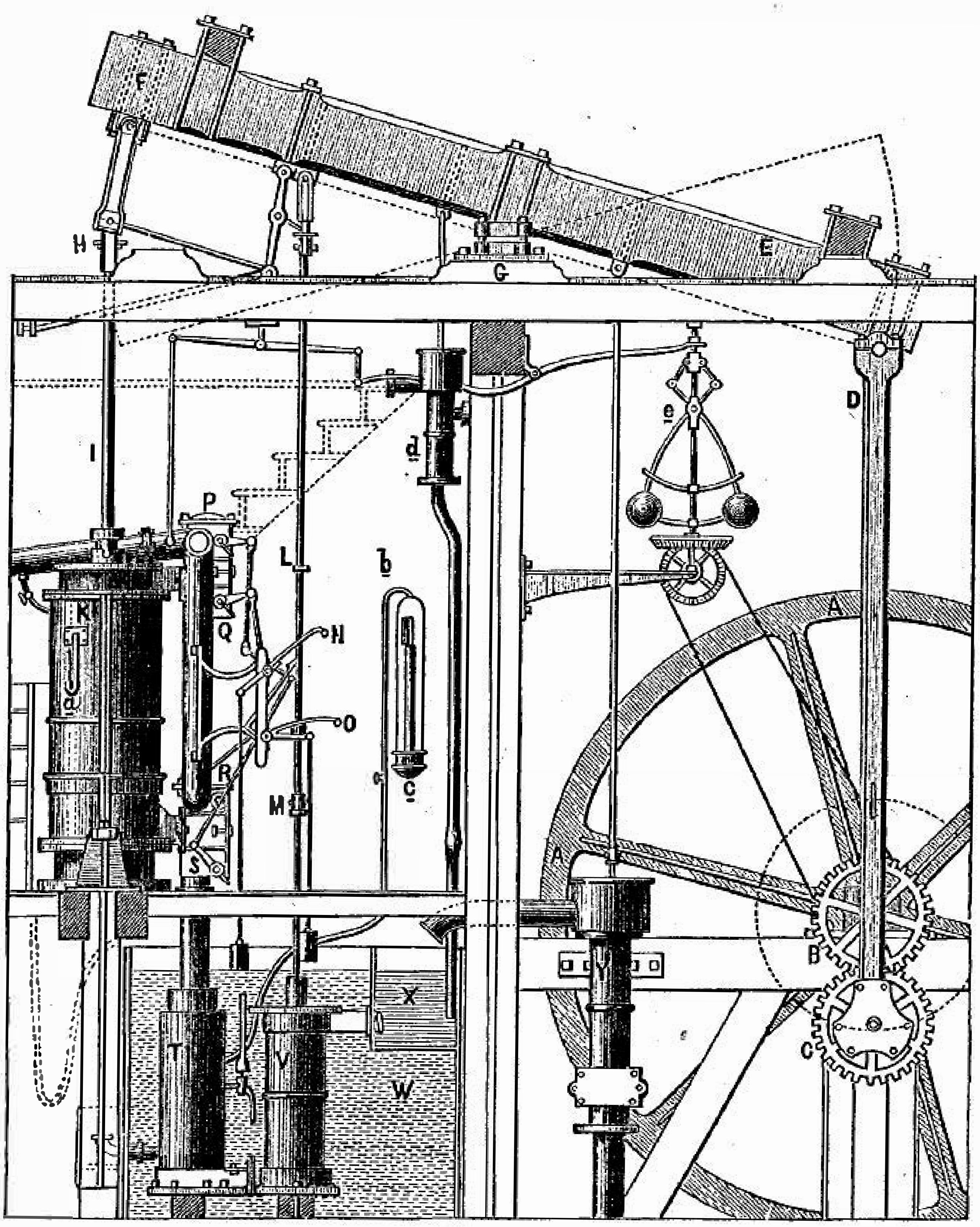


FIG. 27.—Watt's Engine, 1781.

In the following year, October 25, 1781, Watt patented five devices by which he obtained the rotary motion of the engine-shaft without the use of a crank. One of these was the arrangement shown in Fig. 27, and known as the "sun-and-planet" wheels. The crank-shaft carries a gear-wheel, which is engaged by another securely fixed upon the end of the connecting-rod. As the latter is compelled to revolve about the axis of the shaft by a tie which confines the connecting-rod end at a fixed distance from the shaft, the shaft-gear is compelled to revolve, and the shaft with it. Any desired velocity-ratio was secured by giving the two gears the necessary relative diameters. A fly-wheel was used to regulate the motion of the shaft.[1] Boulton & Watt used the sun-and-planet device on many engines, but finally adopted the crank, when the expiration of the patent held by Matthew Wasborough, and which had earlier date than Watt's patent of 1781, permitted them. Watt had proposed the use of a crank, it is said, as early as 1771, but Wasborough anticipated him in securing the patent. Watt had made a model of an engine with a crank and fly-wheel, and he has stated that one of his workmen, who had seen the model, described it to Wasborough, thus enabling the latter to deprive Watt of his own property. The proceeding excited great indignation on the part of Watt; but no legal action was taken by Boulton & Watt, as the overthrow of the patent was thought likely to do them injury by permitting its use by more active competitors and more ingenious men.

The next patent issued to Watt was an exceedingly important one, and of especial interest in a history of the development of the economical application of steam. This patent included:

1. The expansion of steam, and six methods of applying the principle and of equalizing the expansive power.

2. The double-acting steam-engine, in which the steam acts on each side the piston alternately, the opposite side being in communication with the condenser.

[1] For the privilege of using the fly-wheel to regulate the motion of the engine, Boulton & Watt paid a royalty to Matthew Wasborough, who had patented it, and who held also the patent for its combination with a crank, as invented by Pickard and Steed.

3. The double or coupled steam-engine—two engines capable of working together, or independently, as may be desired.

4. The use of a rack on the piston-rod, working into a sector on the end of the beam, thus securing a perfect rectilinear motion of the rod.

5. A rotary engine, or "steam-wheel."

The efficiency to be secured by the expansion of steam had long been known to Watt, and he had conceived the idea of economizing some of that power, the waste of which was so plainly indicated by the violent rushing of the exhaust-steam into the condenser, as early as 1769. This was described in a letter to Dr. Small, of Birmingham, in May of that year. When experimenting at Kinneil, he had tried to determine the real value of the principle by trial on his small engine.

Boulton had also recognized the importance of this improved method of working steam, and their earlier Soho engines were, as Watt said, made with cylinders "double the size wanted, and cut off the steam at half-stroke." But, though "this was a great saving of steam, so long as the valves remained as at first," the builders were so constantly annoyed by alterations of the valves by proprietors and their engineers, that they finally gave up that method of working, hoping ultimately to be able to resume it when workmen of greater intelligence and reliability could be found. The patent was issued July 17, 1782.

Watt specified a cut-off at one-quarter stroke as usually best.

Watt's explanation of the method of economizing by expansive working, as given to Dr. Small,[1] is worthy of reproduction. He says: "I mentioned to you a method of still doubling the effect of steam, and that tolerably easy, by using the power of steam rushing into a vacuum, at

[1] "Lives of Boulton and Watt," Smiles.

present lost. This would do a little more than double the effect, but it would too much enlarge the vesselseto use it all. It is peculiarly applicable to wheel-engines, and may supply the want of a condenser where force of steam is only used; for, open one of the steam-valves and admit steam, until one-fourth of the distance between it and the next valve is filled with steam, shut the valve, and the steam will continue to expand and to pass round the wheel with a diminishing power, ending in one-fourth its first exertion. The sum of this series you will find greater than one-half, though only one-fourth steam was used. The power will indeed be unequal, but this can be remedied by a fly, or in several other ways."

It will be noticed that Watt suggests, above, the now well-known non-condensing engine. He had already, as has been seen, described it in his patent of 1769, as also the rotary engine.

Watt illustrates and explains his idea very neatly, by a sketch similar to that here given (Fig. 28).

Steam, entering the cylinder at *a*, is admitted until one-fourth the stroke has been made, when the steam-valve is closed, and the remainder of the stroke iseperformed without further additioneof steam. The variation of steam-pressure is approximately inversely proportional to the variation of its volume. Thus, at half-stroke, the pressure becomes one-half that at which the steam was supplied to the cylinder. At the end of the stroke it has fallen to one-fourth the initial pressure. The pressure is always nearly equal to the product of the initial pressure and volume divided by the volume at the given instant. In symbols,

$$P' = \frac{PV}{V'}.$$

It is true that the condensation of steam doing work changes this law in a marked manner; but the condensation and reëvaporation of steam, due to the transfer of heat to and from the metal of the cylinder, tends to compensate the first variation by a reverse change of pressure with change of volume.

The sketch shows this progressive variation of pressure as expansion proceeds. It is seen that the work done per unit of volume of steam as taken from the boiler is much

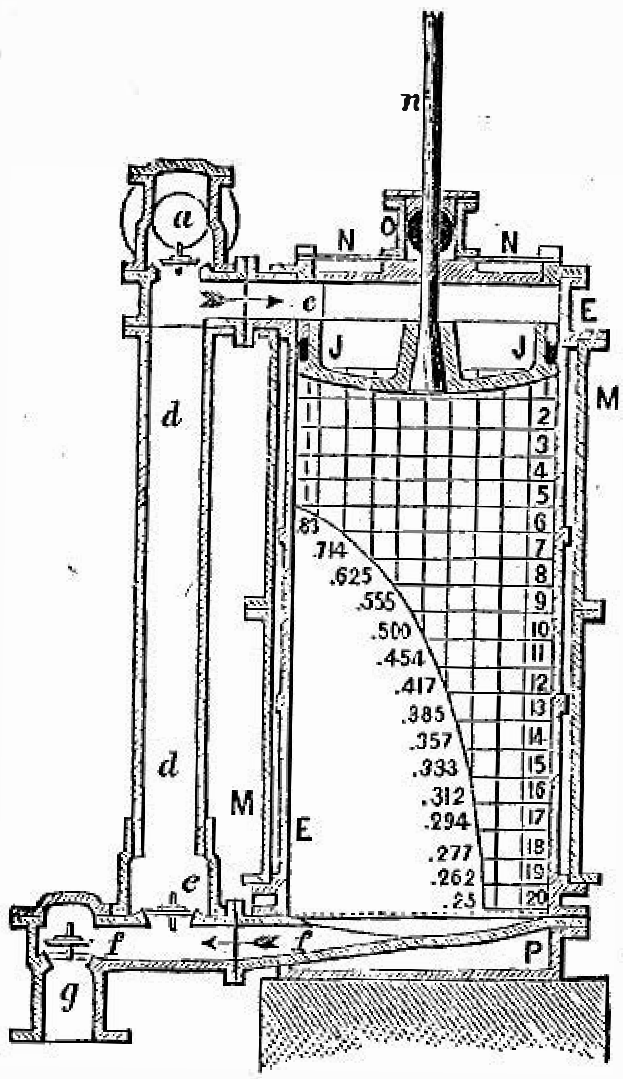


FIG. 28.—Expansion of Steam.

greater than when working without expansion. The product of the mean pressure by the volume of the cylinder is less, but the quotient obtained by dividing this quantity by the volume or weight of steam taken from the boiler, is much greater with than without expansion. For the case assumed and illustrated, the work done during expansion is one and two-fifths times that done previous to cutting off the steam, and the work done per pound of steam is 2.4 times that done without expansion.

Were there no losses to be met with and to be exaggerated by the use of steam expansively, the gain would become very great with moderate expansion, amounting to twice the work done when "following" full stroke, when the steam is cut off at one-seventh. The estimated gain is, however, never realized. Losses by friction, by conduction and radiation of heat, and by condensation and reëvaporation in the cylinder—of which losses the latter are most serious—after passing a point which is variable, and which is determined by the special conditions in each case, augment with greater rapidity than the gain by expansion.

In actual practice, it is rarely found, except where special precautions are taken to reduce these losses, that economy follows expansion to a greater number of volumes than about one-half the square root of the steam-pressure; i. e., about twice for 15 or 20 pounds pressure, three times for about 30 pounds, and four and five times for 60 or 65 and for 100 to 125 pounds respectively. Watt very soon learned this general principle; but neither he, nor even many modern engineers, seem to have learned that too great expansion often gives greatly-reduced economy.

The inequality of pressure due to expansion, to which he refers, was a source of much perplexity to Watt, as he was for a long time convinced that he must find some method of "equalizing" the consequent irregular effort of the steam upon the piston. The several methods of "equalizing the expansive power" which are referred to in the patent were attempts to secure this result. By one method, he shifted the centre as the beam vibrated, thus changing the lengths of the arms of that great lever, to compensate the change of moment consequent upon the change of pressure. He finally concluded that a fly-wheel, as first proposed by Fitzgerald, who advised its use on Papin's engine, would be the best device on engines driving a crank, and trusted to the inertia of a balance-weight in his pumping-engines, or to the weight of the pump-rods, and permitted the piston to take its own speed so far as it was not thus controlled.

The double-acting engine was a modification of the single-acting engine, and was very soon determined upon after the successful working of the latter had become assured.

Watt had covered in the top of his single-acting engine, to prevent cooling the interioreof the cylinder by contact with the comparatively cold atmosphere. When this had been done, there was but a single step required to convert the machine into the double-acting engine. This alteration, by which the steam was permitted to act upon the upper and the lower sides of the piston alternately, had been proposed by Watt as early as 1767, and a drawing of the engine was laid before a committee of the House of Commons in 1774–'75. By this simple change Watt doubled the power of his engine. Although invented much earlier, the plan was not patented until he was, as he states, driven to take out the patent by the "plagiarists and piratesd" who were always ready to profit by his ingenuity. This form of engine is now almost universally used. The single-acting pumping-engine remains in use in Cornwall, and in a few other localities, and now and then an engine is built for other purposes, in which steam acts only on one side of the piston; but these are rare exceptions to the general rule.

The subject of his next invention was not less interesting. The double-cylinder or "compound" engine has now, after the lapse of nearly a century, become an important and usual type of engine. It is impossible to determine precisely to whom to award the credit of its first conception. Dr. Falk, in 1779, had proposed a double-acting engine, in which there were two single-acting cylinders, acting in opposite directions and alternately on opposite sides of a wheel, with which a rack on the piston-rod of each geared.

Watt claimed that Hornblower, the patentee of the "compound engine," was an infringer upon his patentse and, holding the patent on the separate condenser, he was able to prevent the engine of his competitor taking such form as to be successfully introduced. The Hornblower engine was soon given up.

Watt stated that this form of engine had been invented by him as early as 1767, and that he had explained its peculiarities to Smeaton and others several years before Hornblower attempted to use it. He wrote to Boulton: "It is no less than our double-cylinder engine, worked upon our principle of expansion." He never made use of the plan, however, and the principal object sought, apparently, in patenting this, as well as many other devices, was to secure himself against competition.

The rack and sector patented at this time was soon superseded by the parallel-motion, and the last claim, the "steam-wheel" or rotary engine, although one was built of considerable size, was not introduced.

After the patent of 1782 had been secured, Watt turned his attention, when not too hard-pressed by business, to other schemes, and to experimenting with still other modifications and applications of his engine. He had, as early as 1777, proposed to make a steam-hammer for Wilkinson's forge; but he was too closely engaged with more important matters to take hold of the project with much earnestness until late in the year 1782, when, after some preliminary trials, he reported, December 13th: "We have tried our little tilting-forge hammer at Soho with success. The following are some of the particulars: Cylinder, 15 inches in diameter; 4 feet stroke; strokes per minute, 20. The hammer-head, 120 pounds weight, rises 8 inches, and strikes 240 blows per minute. The machine goes quite regularly, and can be managed as easily as a water-mill. It requires a very small quantity of steam—not above half the contents of the cylinder per stroke. The power employed is not more than one-fourth of what would be required to raise the quantity of water which would enable a water-wheel to work the same hammer with the same velocity."

He immediately set about making a much heavier hammer, and on April 26, 1783, he wrote that he had done "a thing never done before"—making his hammer strike 300 blows a minute. This hammer weighed $7\frac{1}{2}$ hundredweight, and had a drop of 2 feet. The steam-cylinder had a diameter of 42 inches and 6 feet stroke of piston, and was calculated to have sufficient power to drive four hammers weighing 7 hundredweight each. The engine made 20 strokes per minute, the hammer giving 90 blows in the same time.

This new application of steam-power proving successful, Watt next began to develop a series of minor inventions, which were finally secured by his patent of April 27, 1784, together with the steam tilt-hammer, and a steam-carriage, or "locomotive engine."

The contrivance previously used for guiding the head of the piston-rod—the sectors and chains, or rack—had never given satisfaction. The rudeness of design of the contrivance was only equalled by its insecurity. Watt therefore contrived a number of methods of accomplishing the purpose, the most beautiful and widely-known of which is the "parallel-motion," although it has now been generally superseded by one of the other devices patented at the same time—the cross-head and guides. As originally proposed, a rod was attached to the head of the piston-rod, standing vertically when the latter was at quarter-stroke. The upper end of this rod was pivoted to the end of the beam, and the lower end to the extremity of a horizontal rod having a length equal to one-half the length of the beam. The other end of the horizontal rod was coupled to the frame of the engine. As the piston rose and fell, the upper and lower ends of the vertical rod were swayed in opposite directions, and to an equal extent, by the beam and the lower horizontal rod, the middle point at which the piston-rod was attached preserving its position in the vertical line. This form was objectionable, as the whole effort of the engine was transmitted through the parallel-motion rods. Another form is shown in the sketch given of the double-acting engine in Fig. 31, which was free from this defect. The head of the piston-rod, *g*, was guided by rods connecting it with the frame at *c*, and forming a "parallelogram," *g d e b*, with the beam. Many varieties of "parallel-motions" have been devised since Watt's invention was attached to his engines at Soho. They usually are more or less imperfect, guiding the piston-rod in a line only approximately straight.

The cross-head and guides are now generally used, very much as described by Watt in this patent as his "second principle." This device will be seen in the engravings given hereafter of more modern engines. The head of the piston-rod is fitted into a transverse bar, or cross-head, which carries properly-shaped pieces at its extremities, to which are bolted "gibs," so made as to fit upon guides secured to the engine-frame. These guides are adjusted to precise parallelism with the centre line of the cylinder. The cross-head, sliding in or on these guides, moves in a perfectly straight line, and, compelling the piston-rod to move with it, the latter is even more perfectly guided than by a parallel-motion. This arrangement, where properly proportioned, is not necessarily subject to great friction, and is much more easily adjusted and kept in line than the parallel-motion when wear occurs or maladjustment takes place.

By the same patent, Watt secured the now common "puppet-valves" with beveled seat, and the application of the steam-engine to driving rolling-mills and hammers for forges, and to "wheel-carriages for removing persons or goods, or other matters, from place to place." For the latter purpose he proposes to use boilers "of wood, or of thin metal, strongly secured by hoops or otherwise," and containing "internal fire-boxes." He proposed to use a condenser cooled by currents of air.

It would require too much space to follow Watt in all his schemes for the improvement and for the application of the steam-engine. A few of the more important and more ingenious only can be described. Many of the contracts of

Boulton & Watt gave them, as compensation for their engines, a fraction—usually one-third—of the value of the fuel saved by the use of the Watt engine in place of the engine of Newcomen, the amount due being paid annually or semiannually, with an option of redemption on the part of the purchaser at ten years' purchase. This form of agreement compelled a careful determination, often, of the work done and fuel consumed by both the engine taken out and that put in its place.e It was impossible to rely upon any determination by personal observation of the number of strokes made by the engine. Watt therefore made a "counter," like that now familiar to every one as used on gas-meters. It consistseof a train of wheels moving pointers on several dials, the first dial showing tens, the second hundreds, the third thousands, etc., strokes or revolutions. Motion was communicated to the train by means of a pendulum, the whole being mounted on the beam of the engine, where every vibration produced a swing of the pendulum. Eight dials were sometimes used, the counter being set and locked, and only opened once a year, when the time arrived for determining the work done during the preceding twelvemonth.

The application of his engine to purposes for which careful adjustment of speed was requisite, or where the load was subject to considerable variation, led to the use of a e controlling-valve in the steam-pipe, called the "throttle-valve," which was adjustable by hand, and permitted the supply of steam to the engine to be adjusted at any instant and altered to any desired extent. It is now givenemany forms, but it still is most usually made just as originally designed by Watt. It consists of a circular disk, which just closes up the steam-pipe when set directly across it, or of an elliptical disk, which closes the pipe when standing at an angle of somewhat less than 90° with the line of the pipe. This disk is carried on a spindle extending through the pipe at one side, and carrying on its outer end an arm by means of which it may be turned into any position. When placed with its face in line with the pipe, it offers very little resistance to the flow of steam to the engine. When set in the other position, it shuts off steam entirely and stops the engine. It is placed in such position at any time, that the speed of the engine is just that required at the time. In the engraving of the double-acting engine with fly-wheel (Fig. 31), it is shown at *T*, as controlled by the governor.

The governor, or "fly-ball governor," as it is often

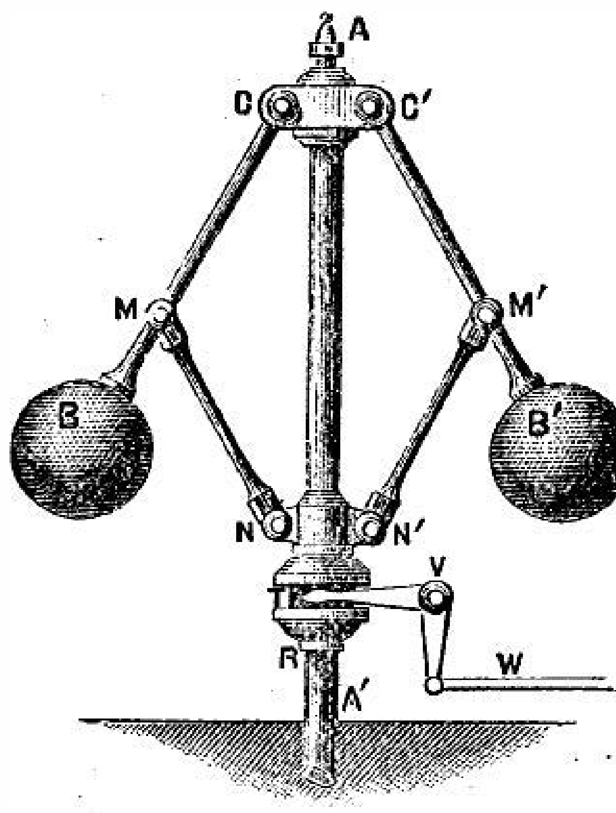


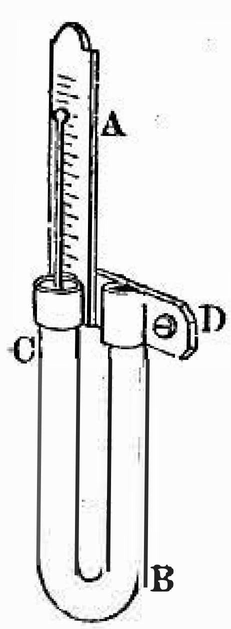
FIG. 29.—The Governor.

distinctively called, was another of Watt's minor but very essential inventions. Two heavy iron or brass balls, *B B′*, were suspended from pins, *C C′*, in a little cross-piece carried on the head of a vertical spindle, *A A′*, driven by the engine. The speed of the engine varying, that of the spindle changed correspondingly, and the faster the balls were swung the farther they separated. When the engine's speed decreased, the period of revolution of the balls was increased, and they fell back toward the spindle. Whenever the velocity of the engine was uniform, the balls preserved their distance from the spindle and remained at the same height, their altitude being determined by the relation existing between the force of gravity and centrifugal force in the temporary position of equilibrium. The distance from the point of suspension down to the level of the balls is always equal to 9.78 inches divided by the square of the number of revolutions per second—i. e., $h = 9.78\frac{1}{N^2} = 0.248\frac{1}{N^2}$ meters.

The arms carrying the balls, or the balls themselves, are pinned to rods, MM', which are connected to a piece, NN', sliding loosely on the spindle. A score, T, cut in this piece engages a lever, V, and, as the balls rise and fall, a rod, W, is moved, closing and opening the throttle-valve, and thus adjusting the supply of steam in such a way as to preserve a nearly fixed speed of engine. The connection with the throttle-valve and with the cut-off valve-gear is seen not only in the engraving of the double-acting Watt engine, but also in those of the Greene and the Corliss engines. This contrivance had previously been used in regulating water-wheels and windmills. Watt's invention consisted in its application to the regulation of the steam-engine.

Still another useful invention of Watt's was his "mercury steam-gauge"—a barometer in which the height of the mercury was determined by the pressure of the steam instead of that of the atmosphere. This simple instrument consisted merely of a bent tube containing a portion of mercury. One leg, BD, of this U-tube was connected with the steam-pipe, or with the boiler by a small steam-pipe; the other end, C, was open to the atmosphere. The pressure of the steam on the mercury in BD caused it to rise in the other "leg" to a height exactly proportioned to the pressure, and causing very nearly two inches difference of level to the pound, or one inch to the pound actual rise in the outer leg. The rude sketch from Farey, here given (Fig. 30), indicates sufficiently well the form of this gauge. It is still considered by engineers the most reliable of all forms of steam-gauge. Unfortunately, it is not conveniently applicable at high pressure. The scale, A, is marked with numbers indicating the pressure, which numbers are indicated by the head of a rod floating up with the mercury.

A similar gauge was used to determine the degree of perfection of vacuum attained in the condenser, the mercury falling in the outer leg as the vacuum became more complete. A perfect vacuum would cause a depression of level in that leg to 30 inches below the level of the mercury in the leg connected with the condenser. In a more usual form, it consisted of a simple glass tube having its lower end immersed in a cistern of mercury, as in the ordinary barometer, the top of the tube being connected with a pipe leading to the condenser. With a perfect vacuum in the condenser, the mercury would rise in the tube very nearly 30 inches. Ordinarily, the vacuum is not nearly perfect, and, a back pressure remaining in the condenser of one or two pounds per square inch, the atmospheric pressure remaining unbalanced is only sufficient to raise the mercury 26 or 28 inches above the level of the liquid metal in the cistern.



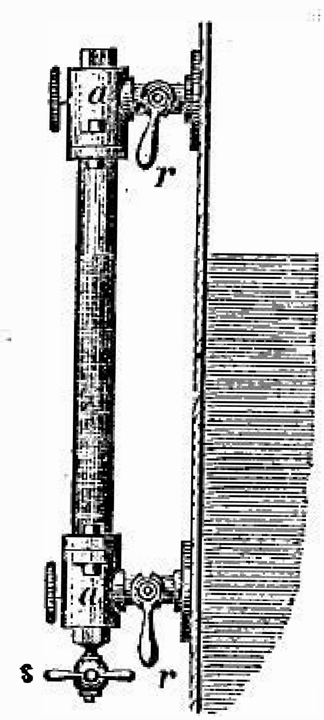


FIG. 30.

Mercury Steam-Gauge. Glass Water-Gauge.

To determine the height of water in his boiler, Watt added to the gauge-cocks already long in use the "glass water-gauge," which is still seen in nearly every well-arranged boiler. This was a glass tube, *a a'* (Fig. 30), mounted on a standard attached to the front of the boiler, and at such a height that its middle point was very little below the proposed water-level. It was connected by a small pipe, *r*, at the top to the steam-space, and another little pipe, *r'*, led into the boiler from its lower end below the water-line. As the water rose and fell within the boiler, its level changed correspondingly in the glass. This little instrument is especially liked, because the position of the water is at all times shown to the eye of the attendant. If carefully protected against sudden changes of temperature, it answers perfectly well with even very high pressures.

The engines built by Boulton & Watt were finally fitted with the crank and fly-wheel for application to the driving of mills and machinery. The accompanying engraving (Fig. 31) shows the engine as thus made, combining all of the essential improvements designed by its inventor.

In the engraving, *C* is the steam-cylinder, *P* the piston, connected to the beam by the link, *g*, and guided by the parallel-motion, *g d c*. At the opposite end of the beam a connecting-rod, *O*, connects with the crank and fly-wheel shaft. *R* is the rod of the air-pump, by means of which the condenser is kept from being flooded by the water used for condensation, which water-supply is regulated by an "injection-handle," *E*. A pump-rod, *N*, leads down from the beam to the cold-water pump, by which water is raised from the well or other source to supply the needed injection-water. The air-pump rod also serves as a "plug-rod," to work the valves, the pins at *m* and *R* striking the lever, *m*, at either end of the stroke. When the piston reaches the top of the cylinder, the lever, *m*, is raised, opening the steam-valve, *B*, at the top, and the exhaust-valve, *E*, at the bottom, and at the same time closing the exhaust at the top and the steam at the bottom. When the entrance of steam at the top and the removal of steam-pressure below the piston has driven the piston to the bottom, the pin, *R*, strikes the lever, *m*, opening the steam and closing the exhaust valve at the bottom, and similarly reversing the position of the valves at the top. The position of the valves is changed in this manner with every reversal of the motion of the piston as the crank "turns over the centre."

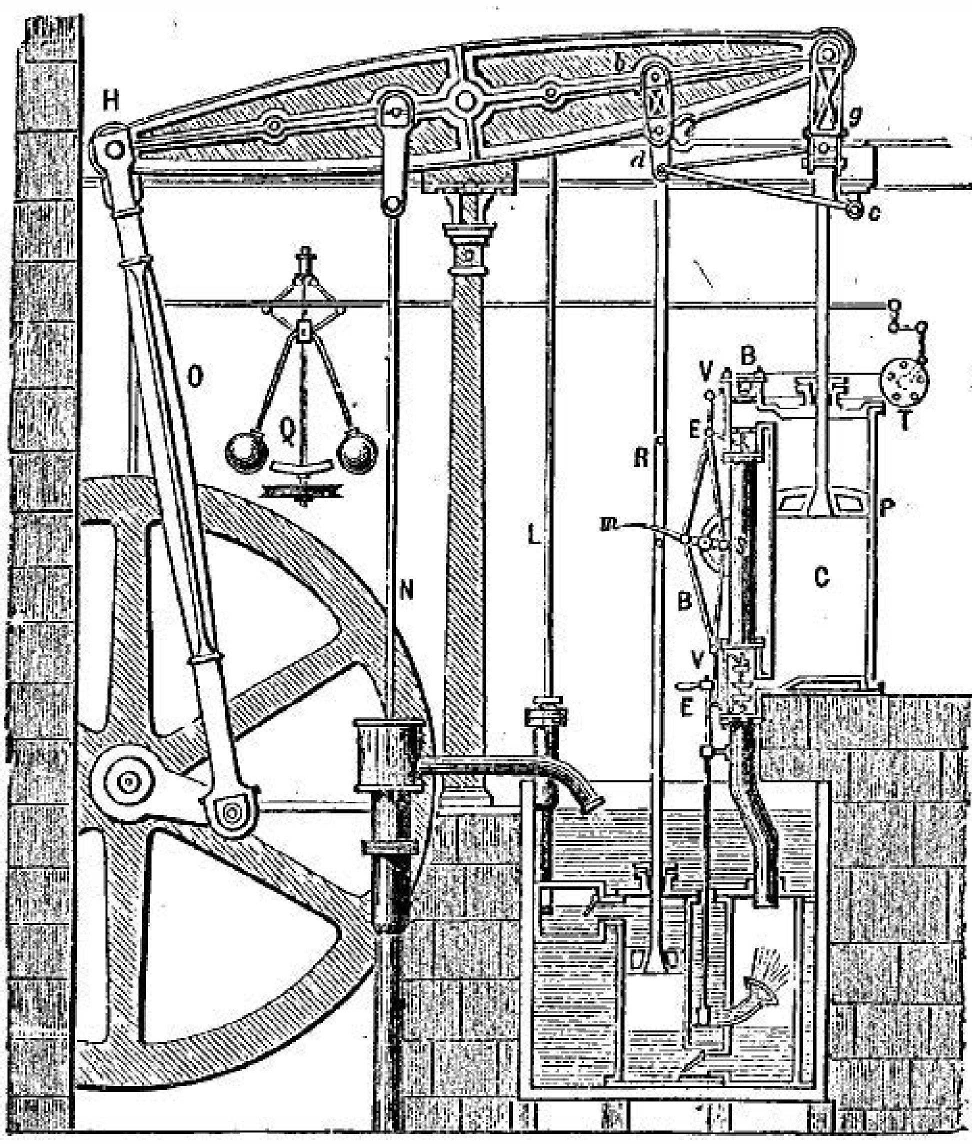


FIG. 31.—Boulton & Watt's Double-Acting Engine, 1784.

The earliest engines of the double-acting kind, and of any considerable size, which were built to turn a shaft, were those which were set up in the Albion Mills, near Blackfriars' Bridge, London, in 1786, and destroyed when the mills burned down in 1791. There were a pair of these engines (shown in Fig. 27), of 50 horse-power each, and geared to drive 20 pairs of stones, making fine flour and meal. Previous to the erection of this mill the power in all such establishments had been derived from windmills and water-wheels. This mill was erected by Boulton & Watt, and capitalists working with them, not only to secure the profit anticipated from locating a flour-mill in the city of London, but also with a view to exhibiting the capacity of the new double-acting "rotatinge" engine. The plan was proposed in 1783, and work was commenced in 1784; but the mill was not set in operation until the spring of 1786. The capacity of the mill was, in ordinary work, 16,000 bushels of wheat ground into fine flour per week.e On one occasion, the mill turned out 3,000 bushels in 24 hours. In the construction of the machinery of the mill, many improvements upon the then standard practice were introduced, including cast-iron gearing with carefully-formed teeth and iron framing. It was here that John Rennie commenced his work, after passing through his apprenticeship in Scotland, sending his chief assistant, Ewart, to superintend the erection of the milling machinery. The mill was a success as a piece of engineering, but a serious loss was incurred by the capitalists engaged in the enterprise, as it was set on fire a few years afterward and entirely destroyed. Boulton and Watt were the principal losers, the former losing £6,000, and the latter £3,000.

The valve-gear of this engine, a view of which is given in Fig. 27, was quite similar to that used on the Watt pumping-engine. The accompanying illustration (Fig. 32) represents this valve-motion as attached to the Albion Mills engine.

The steam-pipe, *a b d d e*, leads the steam from the boiler to the chambers, *b* and *e*. The exhaust-pipe, *g g*, leads from *h* and *i* to the condenser. In the sketch, the upper steam and the lower exhaust valves, *b* and *f*, are opened, and the steam-valve, *e*, and exhaust-valve, *c*, are closed, the piston being near the upper end of the cylinder and descending. *L* represents the plug-frame, which carries tappets, 2 and 3, which engage the lever, *s*, at either end of its throw, and turn the shaft, *u*, thus opening and closing *c* and *e* simultaneously by means of the connecting-links, 13 and

14. A similar pair of tappets on the opposite side of the plug-rod move the valves, *b* and *f*, by means of the rods, 10 and 11, the arm, *r*, when struck by those tappets, turning the shaft, *t*, and thus moving the arms to which those rods are attached. Counterbalance-weights, carried on the ends of the arms, 4 and 15, retain the valves on their seats when closed by the action of the tappets. When the piston nearly reaches the lower end of the cylinder, the tappet, 1,

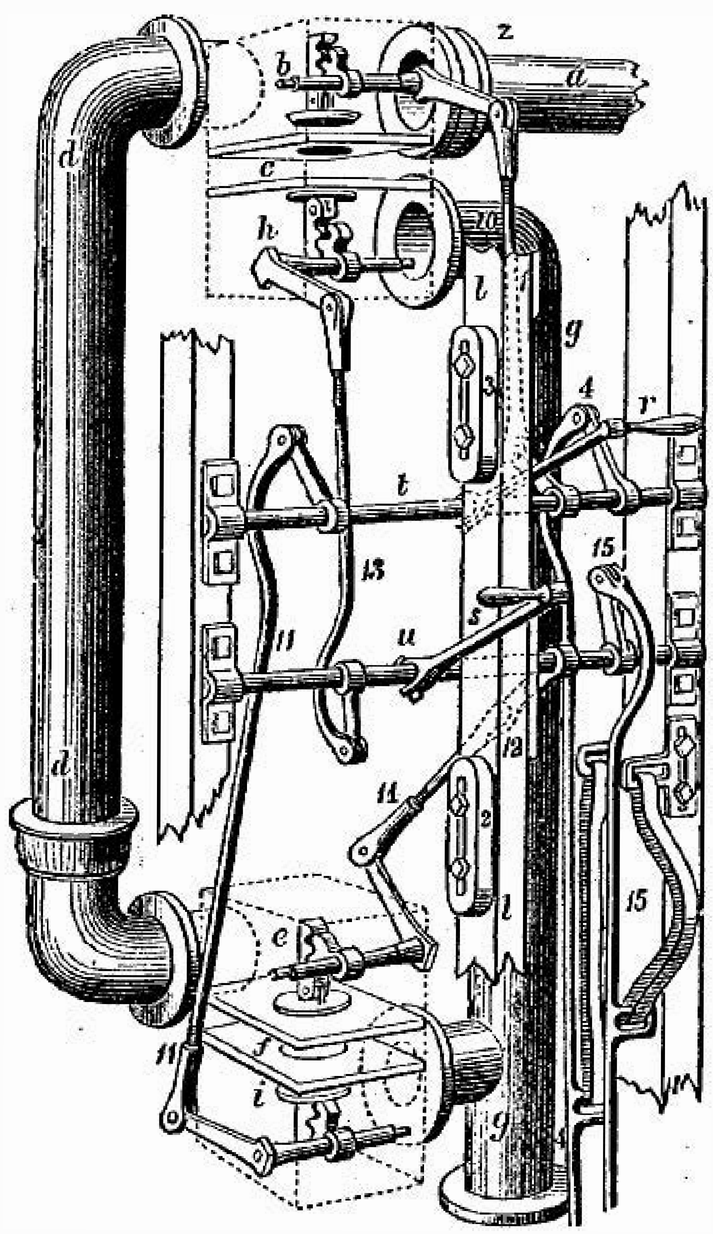


FIG. 32.—Valve-Gear of the Albion Mills Engine.

engages the arm, *r*, closing the steam-valve, *b*, and the next instant shutting the exhaust-valve, *f*. At the same time, the tappet, 3, by moving the arm, *s*, downward, opens the steam-valve, *e*, and the exhaust-valve, *c*. Steam now no longer issues from the steam-pipe into the space, *c*, and thence into the engine-cylinder (not shown in the sketch)e; but it nowe enters the engine through the valve, *e*, forcing the piston upwards. The exhaust is simultaneously made to occur at the upper end, the rejected steam passing from the engine into the space, *c*, and thence through *c* and the pipe, *g*, into the condenser.

This kind of valve-gear was subsequently greatly improved by Murdoch, Watt's ingenious and efficient foreman, buteit is now entirely superseded on engines of this class by the eccentric, and the various forms of valve-gear driven by it.

The "trunk-engine" was still another of the almost innumerable inventions of Watt. A half-trunk engine is described in his patent of 1784, as shown in the accompanying sketch (Fig. 33), in which *A* is the cylinder, *B* the

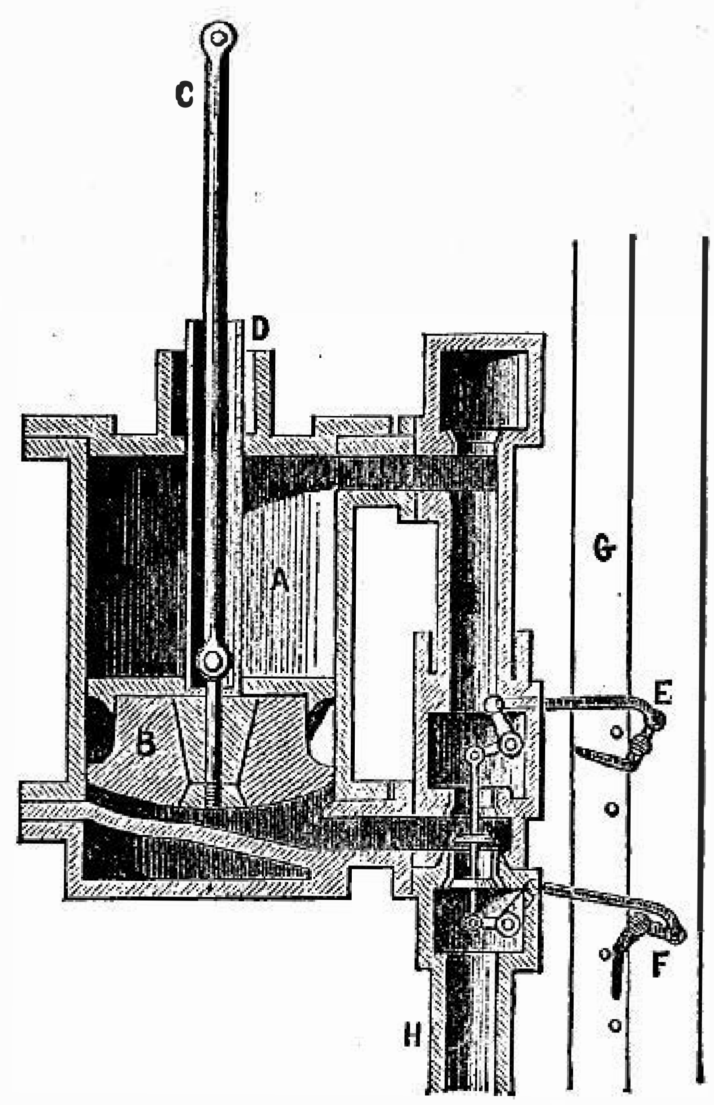


FIG. 33.—Watt's Half-Trunk Engine, 1784.

piston, and *C* its rod, encased in the half-trunk, *D*. The plug-rod, *G*, moves the single pair of valves by striking the catches, *E* and *F*, as was usual with Watt's earlier engines.

Watt's steam-hammer was patented at the same time. It is seen in Fig. 34, in which *A* is the steam-cylinder and *B* its rod, the engine being evidently of the form just described. It works a beam, *C C*, which in turn, by the rod,

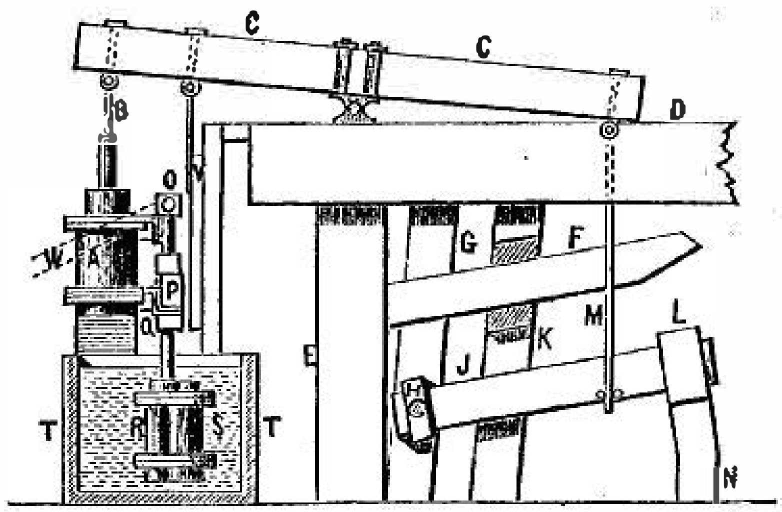


FIG. 34.—The Watt Hammer, 1784.

M, works the hammer-helve, *L J*, and the hammer, *L*. The beam, *F G*, is a spring, and the block, *N*, the anvil.

Watt found it impossible to determine the duty of his engines at all times by measurement of the work itself, and endeavored to find a way of ascertaining the power produced, by ascertaining the pressure of steam within the cylinder. This pressure was so variable, and subject to such rapid as well as extreme fluctuations, that he found it impossible to make use of the steam-gauge constructed for use on the boiler. He was thus driven to invent a special instrument for this work, which he called the "steam-engine indicator." This consisted of a little steam-cylinder containing a nicely-fitting piston, which moved without noticeable friction through a range which was limited by the compression of a helical spring, by means of which the piston was secured to the top of its cylinder. The distance through which the piston rose was proportional to the pressure exerted upon it, and a pointer attached to its rod traversed a scale upon which the pressure per square inch could be read. The lower end of the instrument being connected with the steam-cylinder of the engine by a small pipe fitted with a cock, the opening of the latter permitted steam from the engine-cylinder to fill the indicator-cylinder, and the pressure of steam was always the same in both cylinders. The indicator-pointer therefore traversed the pressure-scale, alwayse exhibiting the pressure existing at the instant in the cylinder of the engine. When the engine was at rest and steam off, the indicator-piston stood at the same level as when detached from the engine, and the pointer stood at 0 on the scale. When steam entered, the piston rose and fell with the fluctuations of pressuree and when the exhaust-valve opened, discharging the steam and producing a vacuum in the steam-cylinder, the pointer of the indicator dropped below 0, showing the degree of exhaustion. Mr. Southern, one of Watt's assistants, fitted the instrument with a sliding board, moved horizontally backward and forward by a cord or link-work connecting directly or indirectly with the engine-beam, and thus giving it a motion coincident with that of the piston. This boardecarried a piece of paper, upon which a pencil attached to the indicator piston-rod drew a curve. The vertical height of any point on this curve above the base-line measured the pressure in the cylinder at the moment when it was made, and the horizontal distance of the point from either end of the diagram determined the position, at the same moment, of the engine-piston. The curve thus inscribed, called theé"indicator card," or indicator diagram, exhibiting every minute change in the pressure of steam in the engine, not only enabled the mean pressure and the power of the engine to be determined by its measurement, but, to the eye of the expert engineer, it was a perfectly legible statement of the position of the valves of the engine, and revealed almost every defect in the action of the engine which could not readily be detected by external examination. It has justly been called the "engineers' stethoscope," opening the otherwise inaccessible parts of the steam-engine to the inspection of the engineer even more satisfactorily than the stethoscope of the physician gives him a knowledge of the condition and working of organs contained within the human body. This indispensable and now familiar engineers' instrument has since been modified and greatly improved in detail.

The Watt engine had, by the construction of the improvements described in the patents of 1782–'85, been given its distinctive form, and the great inventor subsequently did little more than improve it by altering the forms and proportions of its details. As thus practically completed, it embodied nearly all the essential features of the modern engine; and, as we have seen, the marked features of our latest practice—the use of the double cylinder for expansion, the cut-off valve-gear, and surface-condensation—had all been proposed, and to a limited extent introduced. The growth of the steam-engine has here ceased to be rapid, and the changes which followed the completion of the work of James Watt have been minor improvements, and rarely, if ever, real developments.

Watt's mind lost none of its activity, however, for many years. He devised and patented a "smoke-consuming furnace," in which he led the gases produced on the introduction of fresh fuel over the already incandescent coal, and thus burned them completely. He used two fires, which were coaled alternately. Even when busiest, also, he found time to pursue more purely scientific studies. With Boulton, he induced a number of well-known scientific men living near Birmingham to join in the formation of a "Lunar Society," to meet monthly at the houses of its members, "at the full of the moon." The time was thus fixed in order that those members who came from a distance should be able to drive home, after the meetings, by moonlight. Many such societies were then in existence in England; but that at Birmingham was one of the largest and most distinguished of them all. Boulton, Watt, Drs. Small, Darwin, and Priestley, were the leaders, and among their occasional visitors were Herschel, Smeaton, and Banks. Watt called these meetings "Philosophers' meetings." It was during the period of most active discussion at the "philosophers' meetings" that Cavendish and Priestley were experimenting with mixtures of oxygen and hydrogen, to determine the nature of their combustion. Watt took much interest in the subject, and, when informed by Priestley that he and Cavendish had both noticed a deposit of moisture invariably succeeding the explosion of the mixed gases, when contained in a cold vessel, and that the weight of this water was approximately equal to the weight of the mixed gases, he at once came to the conclusion that the union of hydrogen with oxygen produced water, the latter being a chemical compound, of which the former were constituents. He communicated this reasoning, and the conclusions to which it had led him, to Boulton, in a letter written in December, 1782, and addressed a letter some time afterward to Priestley, which was to have been read before the Royal Society in April, 1783. The letter was not read, however, until a year later, and, three months after, a paper by Cavendish, making the same announcement, had been laid before the Society. Watt stated that both Cavendish and Lavoisier, to whom also the discovery is ascribed, received the idea from him.

The action of chlorine in bleaching organic coloring-matters, by (as since shown) decomposing them and combining with their hydrogen, was made known to Watt by M. Berthollet, the distinguished French chemist, and the former immediately introduced its use into Great Britain, by inducing his father-in-law, Mr. Macgregor, to make a trial of it.

The copartnership of Boulton & Watt terminated by limitation, and with the expiration of the patents under which they had been working, in the first year of the present century; and both partners, now old and feeble, withdrew from active business, leaving their sons to renew the agreement and to carry on the business under the same firm-style.

Boulton, however, still interested himself in some branches of manufacture, especially in his mint, where he had coined many years and for several nations.

Watt retired, a little later, to Heathfield, where he passed the remainder of his life in peaceful enjoyment of the society of his friends, in studies of all current matters of interest in science, as well as in engineering. One by one his old friends died—Black in 1799, Priestley, an exile to America, in 1803, and Robison a little later. Boulton died, at the age of eighty-one, August 17, 1809, and even the loss of this nearest and dearest of his friends outside the family was a less severe blow than that of his son Gregory, who died in 1804.

Yet the great engineer and inventor was not depressed by the loneliness which was gradually coming upon him. He wrote: "I know that all men must die, and I submit to the decrees of Nature, I hope, with due reverence to the Disposer of events;" and neglected no opportunity to secure amusement or instruction, and kept body and mind constantly occupied. He still attended the weekly meetings of the club, meeting Rennie and Telford, and other distinguished men of his own and the succeeding generation. He lost nothing of his fondness for invention, and spent many months in devising a machine for copying statuary, which he had not perfected to his own satisfaction at the time of his death, ten years later. This machine was a kind of pentagraph, which could be worked in any plane, and in which the marking-pencil gave place to a cutting-tool. The tracing-point followed the surface of the pattern, while the cutting-point, following its motion precisely, formed a fac-simile in the material operated upon.

In the year 1800 he invented the water-main which was laid down by the Glasgow Water-Works Company across the Clyde. The joints were spherical and articulated, like those of the lobster's tail.

His workshop, of which a sketcheis hereafter given, as drawn by the artist Skelton, was in the garret of his house, and was well supplied with tools and all kinds of laboratory material. His lathe and his copying-machine were placed before the window, and his writing-desk in the corner. Here he spent the greater part of his leisure time, often even taking his meals in the little shop, rather than go to the table for them. Even when very old, he occasionally made a journey to London or Glasgow, calling on his old friends and studying the latest engineering devices and inspecting public works, and was everywhere welcomed by young and old as the greatest living engineer, or as the kind and wise friend of earlier days.

He died August 19, 1819, in the eighty-third year of his age, and was buried in Handsworth Church. The sculptor Chantrey was employed to place a fitting monument above his grave, and the nation erected a statue of the great man in Westminster Abbey.

This sketch of the greatest of all the inventors of the steam-engine has been given no greater length than its subject justifies. Whether we consider Watt as the inventor of the standard steam-engine of the nineteenth century, as the scientific investigator of the physical principles upon which the invention is based, or as the builder and introducer of the most powerful known instrument by which the "great sources of power in Nature are converted, adapted, and applied for the use and convenience of man," he is fully entitled to preëminence. His character as a man was no less admirable than as an engineer.

Smiles, Watt's most conscientious and indefatigable biographer, writes:[1]

"Some months since, we visited the little garret at

[1] "Life of Watt," p. 512.

Heathfield in which Watt pursued the investigations of his later years. The room had been carefully locked

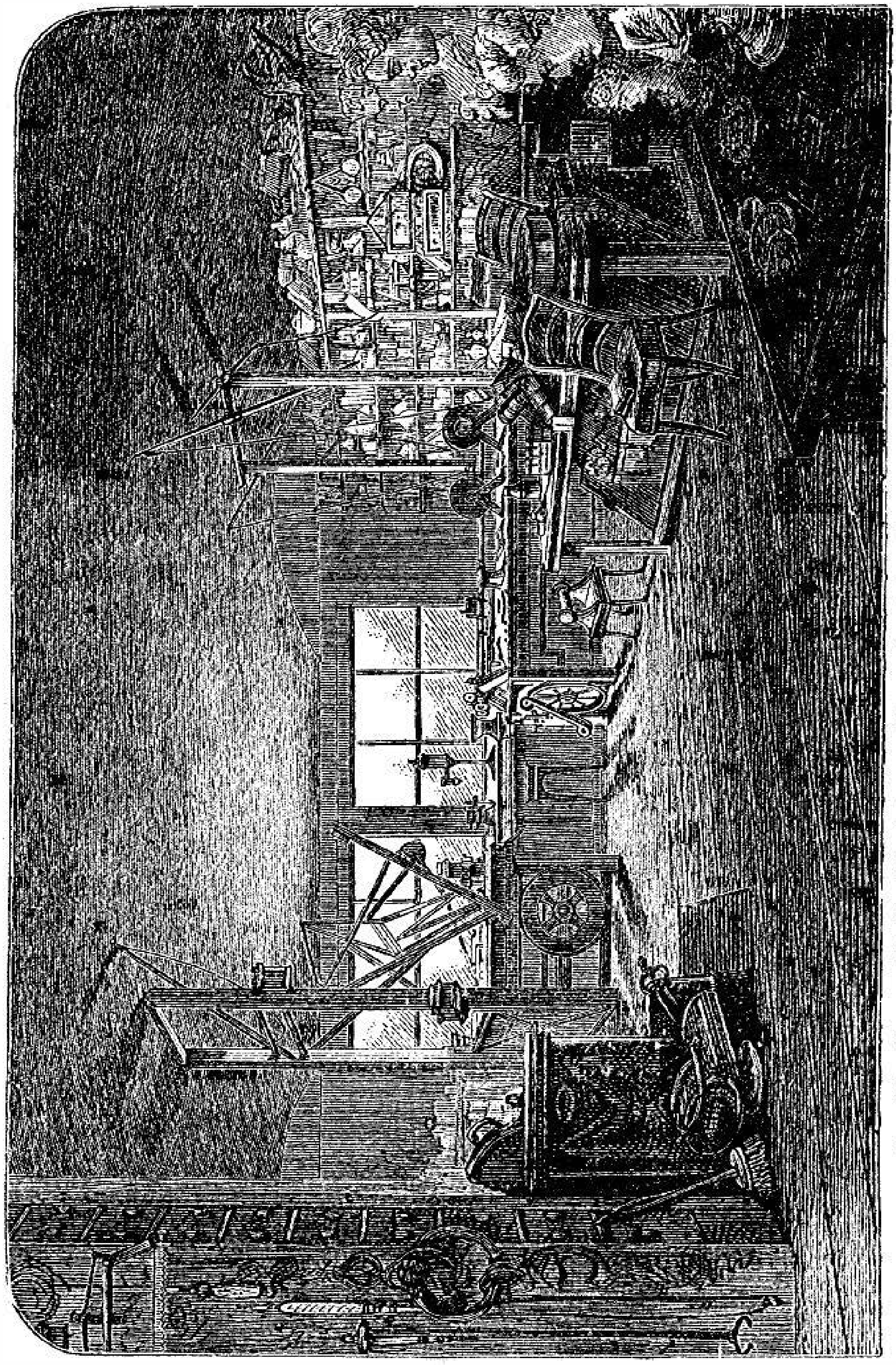


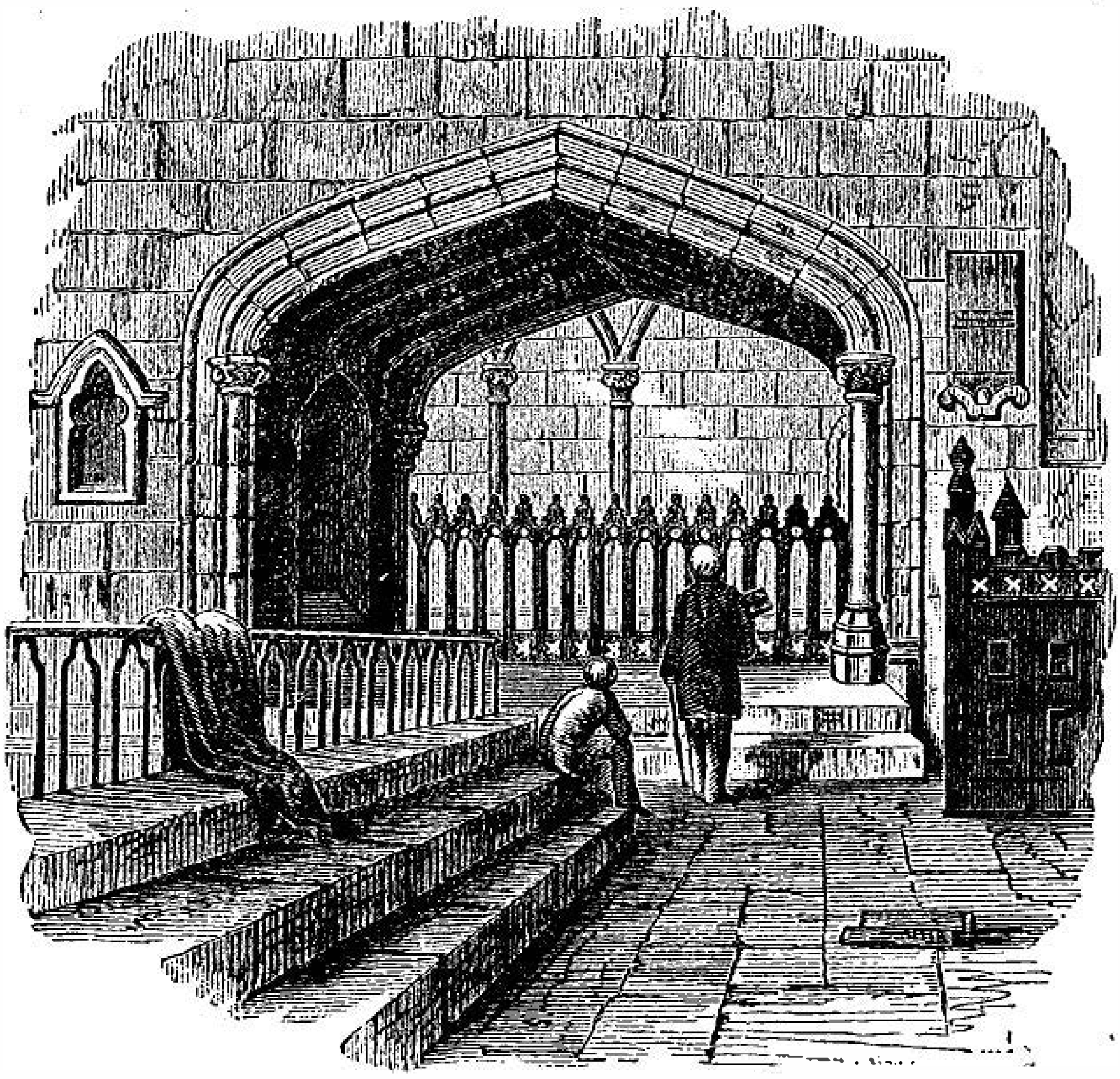
FIG. 35.—James Watt's Workshop. (From Smiles's "Lives of Boulton and Watt.")

up since his death, and had only once been swept out. Everything lay very much as he left it. The piece of iron which he was last employed in turning, lay on the lathe. The ashes of the last fire were in the grate; the laste bit of coal was in the scuttle. The Dutch oven was in its place over the stove, and the frying-pan in which he cooked his meals was hanging on its accustomed nail. Many objects lay about or in the drawers, indicating the pursuits which had been interrupted by death—busts, medallions, and figures, waiting to be copied by the copying-machine—many medallion-moulds, a store of plaster-of-Paris, and a box of plaster casts from London, the contents of which do not seem to have been disturbed. Here are Watt's ladles for melting lead, his foot-rule, his glue-pot, his hammer. Reflecting mirrors, an extemporized camera with the lenses mounted on pasteboard, and many camera-glasses laid about, indicate interrupted experiments in optics. There are quadrant-glasses, compasses, scales, weights, and sundry boxes of mathematical instruments, once doubtless highly prized. In one place a model of the governor, in another of the parallel-motion, and in a little box, fitted with wooden cylinders mounted with paper and covered with figures, is what we suppose to be a model of his calculating-machine. On the shelves are minerals and chemicals in pots and jars, on which the dust of nearly half a century has settled. The moist substances have long since dried up; the putty has been turned to stone, and the paste to dust. On one shelf we come upon a dish in which lies a withered bunch of grapes. On the floor, in a corner, near to where Watt sat and worked, is a hair-trunk—a touching memorial of a long-past love and a long-dead sorrow. It contains all poor Gregory's school-books, his first attempts at writing, his boy's drawings of battles, his first school-exercises down to his college-themes, his delectuses, his grammars, his dictionaries, and his class-books—brought into this retired room, where the father's eye could rest upon them. Near at hand is the sculpture-machine, on which he continued working to the last. Its wooden frame is worm-eaten, and dropping into dust, like the hands that made it. But though the great workman is gone to rest, with all his griefs and cares, and his handiwork is fast crumbling to decay, the spirit of his work, the thought which he put into his inventions, still survives, and will probably continue to influence the destinies of his race for all time to come."

The visitor to Westminster Abbey will find neither monarch, nor warrior, nor statesman, nor poet, honored with a nobler epitaph than that which is inscribed on the pedestal of Chantrey's monument to Watt:

NOT TO PERPETUATE A NAME,
WHICH MUST ENDURE WHILE THE PEACEFUL ARTS FLOURISH,
BUT TO SHOW
THAT MANKIND HAVE LEARNT TO HONOR THOSE WHO BEST DESERVE THEIR GRATITUDE,
THE KING,
HIS MINISTERS, AND MANY OF THE NOBLES AND COMMONERS OF THE REALM,
RAISED THIS MONUMENT TO
JAMES WATT,
WHO, DIRECTING THE FORCE OF AN ORIGINAL GENIUS,
EARLY EXERCISED IN PHILOSOPHIC RESEARCH,
TO THE IMPROVEMENT OF
THE STEAM-ENGINE,
ENLARGED THE RESOURCES OF HIS COUNTRY, INCREASED THE POWER OF MAN,
AND ROSE TO AN EMINENT PLACE
AMONG THE MOST ILLUSTRIOUS FOLLOWERS OF SCIENCE AND THE REAL
BENEFACTORS OF THE WORLD.

BORN AT GREENOCK, MDCCXXXVI.
DIED AT HEATHFIELD, IN STAFFORDSHIRE, MDCCCXIX.



Tomb of James Watt.

SECTION II.—THE CONTEMPORARIES OF JAMES WATT.

In the chronology of the steam-engine, the contemporaries of Watt have been so completely overshadowed by the greater and more successful inventor, as to have been almost forgotten by the biographer and by the student of history. Yet, among the engineers and engine-builders, as well as among the inventors of his day, Watt found many enterprising rivals and keen competitors. Some of these men, had they not been so completely fettered by Watt's patents, would have probably done work which would have entitled them to far higher honor than has been accorded them.

WILLIAM MURDOCH was one of the men to whom Watt, no less than the world, was greatly indebted. For many years he was the assistant, friend, and coadjutor of Watt; and it is to his ingenuity that we are to give credit for not only many independent inventions, but also for the suggestions and improvements which were often indispensable to the formation and perfection of some of Watt's own inventions.

Murdoch was employed by Boulton & Watt in 1776, and was made superintendent of construction in the engine department, and given general charge of the erection of engines. He was sent into Cornwall, and spent in that district much of the time during which he served the firm, erecting pumping-engines, the construction of which for so many years constituted a large part of the business of the Soho establishment. He was looked upon by both Boulton and Watt as a sincere friend, as well as a loyal adherent, and from 1810 to 1830 was given a partner's share of the income of the firm, and a salary of £1,000. He retired from business at the last of the two dates named, and, dying in 1839, was buried near the two partners in Handsworth Church.

Murdoch made a model, in 1784, of the locomotive patented by Watt in that year. He devised the arrangement of "sun-and-planet wheels," adopted for a time in all of Watt's "rotative" engines, and invented the oscillating steam-engine (Fig. 36) in 1785, using the "D-slide valves," *G*, moved by the gear, *E*, which was driven by an eccentric on the shaft, without regard to the oscillation of the cylinder, *A*. He was the inventor of a rotary engine and of many minor machines for special purposes, and of many machine-tools used at Soho in building engines and machines. He seems, like Watt, to have had special fondness for the worm-gear, and introduced it wherever it could properly take the place of ordinary gearing. Some of the machines designed by Watt and Murdoch, who always worked well together, were found still in use and in good working condition by the author when visiting the works at Soho in 1873. The old mint in which, from 1797 to 1805, Boulton had coined 4,000 tons of copper, had then been pulled down, and a new mint had been erected in 1860.

Many old machines still remained about the establishment as souvenirs of the three great mechanics.

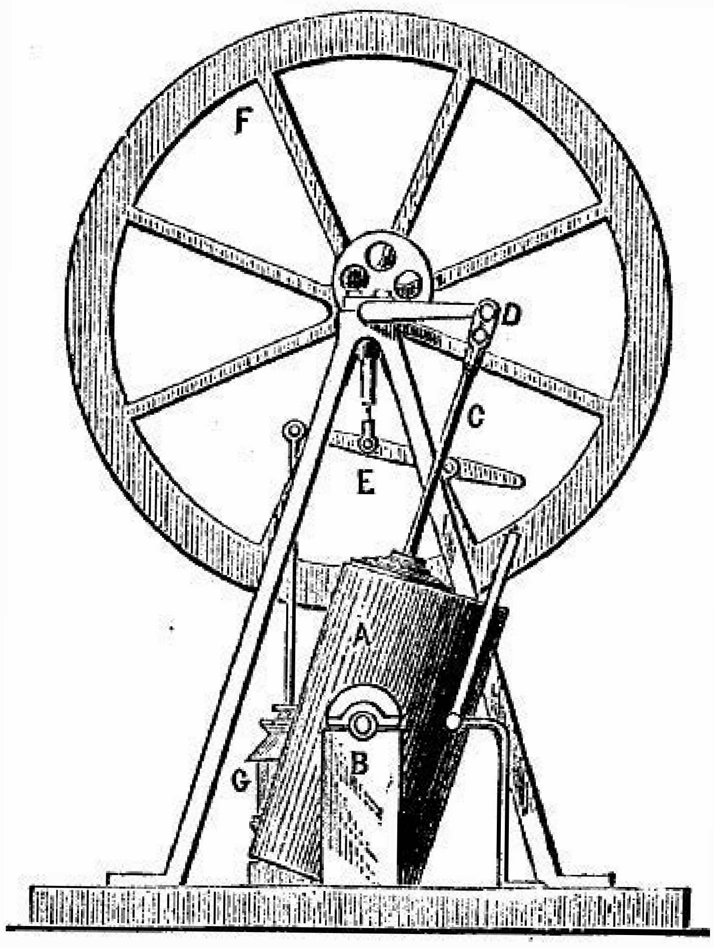


FIG. 36.—Murdoch's Oscillating Engine, 1785.

Outside of Soho, Murdoch also found ample employment for his inventive talent. In 1792, while at Redruth, his residence before finally returning to Soho, he was led to speculate upon the possibility of utilizing the illuminating qualities of coal-gas, and, convinced of its practicability, he laid the subject before the Royal Society in 1808, and was awarded the Rumford gold medal. He had, ten years earlier, lighted a part of the Soho works with coal-gas, and in 1803 Watt authorized him to extend his pipes throughout all the buildings. Several manufacturers promptly introduced the new light, and its use extended very rapidly.

Still another of Murdoch's favorite schemes was the transmission of power by the use of compressed air. He drove the pattern-shop engine at Soho by means of air from the blowing-engine in the foundery, and erected a pneumatic lift to elevate castings from the foundery-floor to the canalbank. He made a steam-gun, introduced the heating of buildings by the circulation of hot water, and invented the method of transmitting packages through tubes by the impulse of compressed air, as now practised by the "pneumatic dispatch" companies. He died at the age of eighty-five years.

Among the most active and formidable of Watt's business rivals was JONATHAN HORNBLOWER, the patentee of the "compounded" or double-cylinder engine. A sketch of this engine, as patented by Hornblower in 1781, is here given (Fig. 37). It was first described by the inventor in the "Encyclopædia Britannica." It consists, as is seen by reference to the engraving, of two steam-cylinders, *A* and *B*—*A* being the low and *B* the high pressure cylinder—the steam leaving the latter being exhausted into the former, and, after doing its work there, passing into the condenser, as already described. The piston-rods, *C* and *D*, are both connected to the same part of the beam by chains, as in the other early engines. These rods pass through stuffing-boxes in the cylinder-heads, which are fitted up like those seen on the Watt engine. Steam is led to the engine through the pipe, *G Y*, and cocks, *a*, *b*, *c*, and *d*, are adjustable, as required, to lead steam into and from the cylinders, and are moved by the plug-rod, *W*, which actuates handles not shown. *K* is the exhaust-pipe leading to the condenser. *V* is the engine feed-pump rod, and *X* the great rod carrying the pump-buckets at the bottom of the shaft.

The cocks *c* and *a* being open and *b* and *d* shut, the steam passes from the boiler into the upper part of the steam-cylinder, *B*; and the communication between the lower part of *B* and the top of *A* is also open. Before starting, steam being shut off from the engine, the great weight of the pump-rod, *X*, causes that end of the beam to preponderate, the pistons standing, as shown, at the top of their respective steam-cylinders.

The engine being freed from all air by opening all the valves and permitting the steam to drive it through the engine and out of the condenser through the "snifting-valve," *O*, the valves *b* and *d* are closed, and the cock in the exhaust-pipe opened.

The steam beneath the piston of the large cylinder is immediately condensed, and the pressure on the upper side

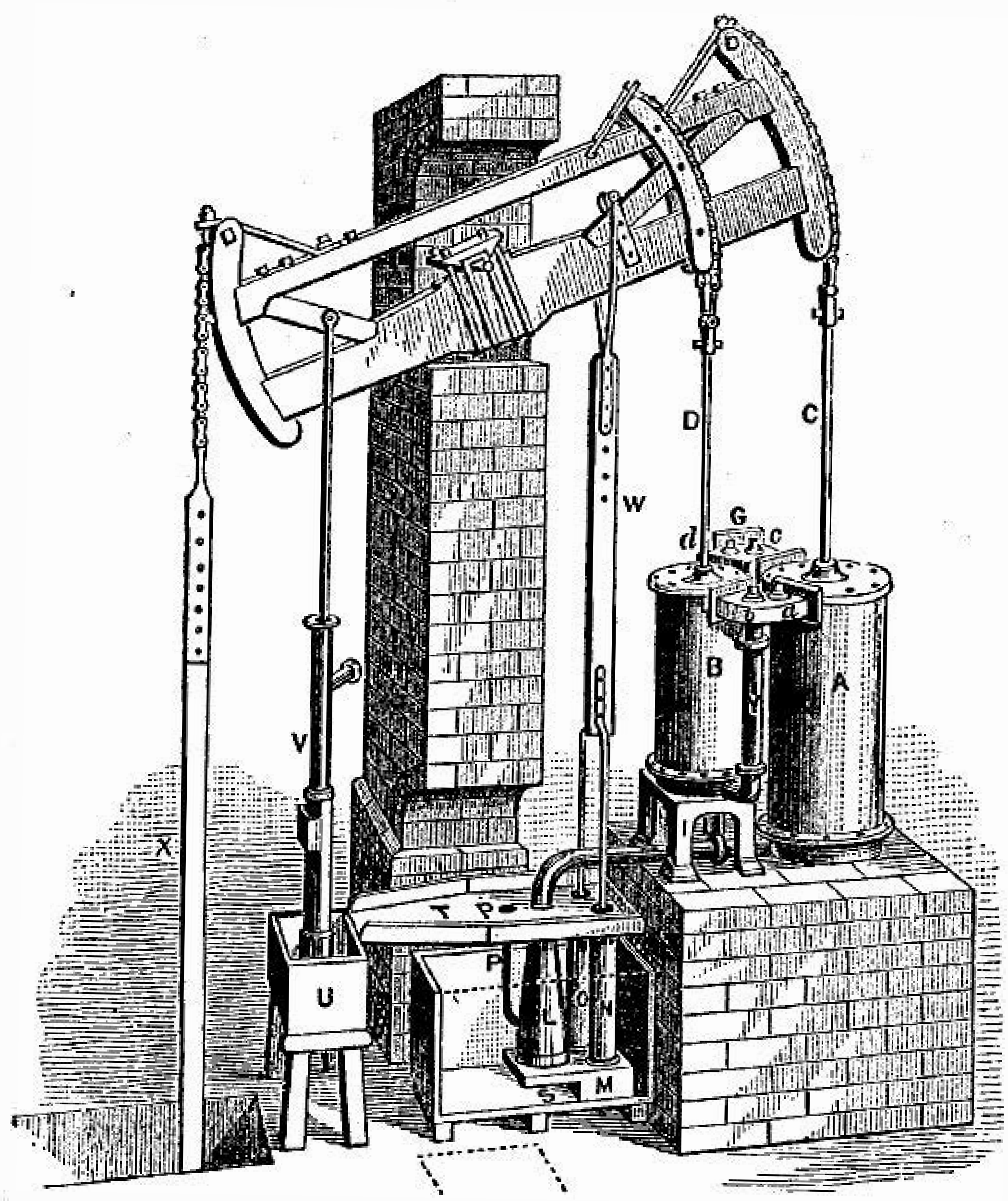


FIG. 87.—Hornblower's Compound Engine, 1781.

of that piston causes it to descend, carrying that end of the beam with it, and raising the opposite end with the pump-rods and their attachments. At the same time, the steam from the lower end of the small high-pressure cylinder being let into the upper end of the larger cylinder, the completion of the stroke finds a cylinder full of steam transferred from the one to the other with corresponding increase of volume and decrease of pressure. While expanding and diminishing in pressure as it passes from the smaller into the largere cylinder, this charge of steam gradually resists less and less the pressure of the steam from the boiler on the upper side of the piston of the small cylinder, *B*, and the net result is the movement of the engine by pressures exerted on the upper sides of both pistons and against pressures of less intensity on the under sides of both. The pressures in the lower part of the small cylinder, in the upper part of the large cylinder, and in the communicating passage, are evidently all equal at any given time.

When the pistons have reached the bottoms of their respective cylinders, the valves at the top of the small cylinder, *B*, and at the bottom of the large cylinder, *A*, are closed, and the valves *c* and *d* are opened. Steam from the boiler now enters beneath the piston of the small cylinder; the steam in the larger cylinder is exhausted into the condenser, and the steam already in the small cylinder passes over into the large cylinder, following up the piston as it rises.

Thus, at each stroke a small cylinder full of steam is taken from the boiler, and the same weight, occupying the volume of the larger cylinder, is exhausted into the condenser from the latter cylinder.

Referring to the method of operation of this engine, Prof. Robison demonstrated that the effectnproduced was the same as in Watt's single-cylinder engine--a fact which is comprehended in the law enunciated many years later by Rankine, that, "so far as the theoretical action of the steam on the piston is concerned, it is immaterial whether the expansion takes place in one cylinder, or in two or more cylinders." It was found, in practice, that the Hornblower engine was no more economical than the Watt engine; and that erected at the Tin Croft Mine, Cornwall, in 1792, did even less work with the same fuel than the Watt engines.

Hornblower was prosecuted by Boulton & Watt for infringement. The suit was decided against him, and he was imprisoned in default of payment of the royalty, and fine demanded. He died a disappointed and impoverished man. The plan thus unsuccessfully introduced by Hornblower was subsequently modified and adopted by others among the contemporaries of Watt; and, with higher steam and the use of the Watt condenser, the "compound" gradually became a standard type of steam-engine.

Arthur Woolf, in 1804, re-introduced the Hornblower or Falck engine, with its two steam-cylinders, using steam of higher tension. His first engine was built for a brewery in London, and a considerable number were subsequently made. Woolf expanded his steam from six to nine times, and the pumping-engines built from his plans were said to have raised about 40,000,000 pounds one foot high per bushel of coals, when the Watt engine was raising but little more than 30,000,000. In one case, a duty of 57,000,000 was claimed.

The most successful of those competitors of Watt who endeavored to devise a peculiar form of pumping-engine, which should have the efficiency of that of Boulton & Watt, and the necessary advantage in first cost, were WILLIAM BULL and RICHARD TREVITHICK.[1] The accompanying illustration shows the design, which was then known as the "Bull Cornish Engine."

The steam-cylinder, *a*, is carried on wooden beams, *b*, extending across the engine-house directly over the pump-well. The piston-rod, *c*, is secured to the pump-rods, *d d*, the cylinder being inverted, and the pumps, *e*, in the shaft, *f*, are thus operated without the intervention of the beam invariably seen in Watt's engines. A connecting-rod, *g*, attached to the pump-rod and to the end of a balance-beam, *h*, operates the latter, and is counterbalanced by a weight, *i*. The rod, *j*, serves both as a plug-rod and as an air-pump connecting-rod. A snifting-valve, *k*, opens

[1] For an exceedingly interesting and very faithful account of their work, *see* "Life of Richard Trevithick," by F. Trevithick, London, 1872.

when the engine is blown through, and relieves the condenser and air-pump, *l*, of all air. The rod, *m*, operates a

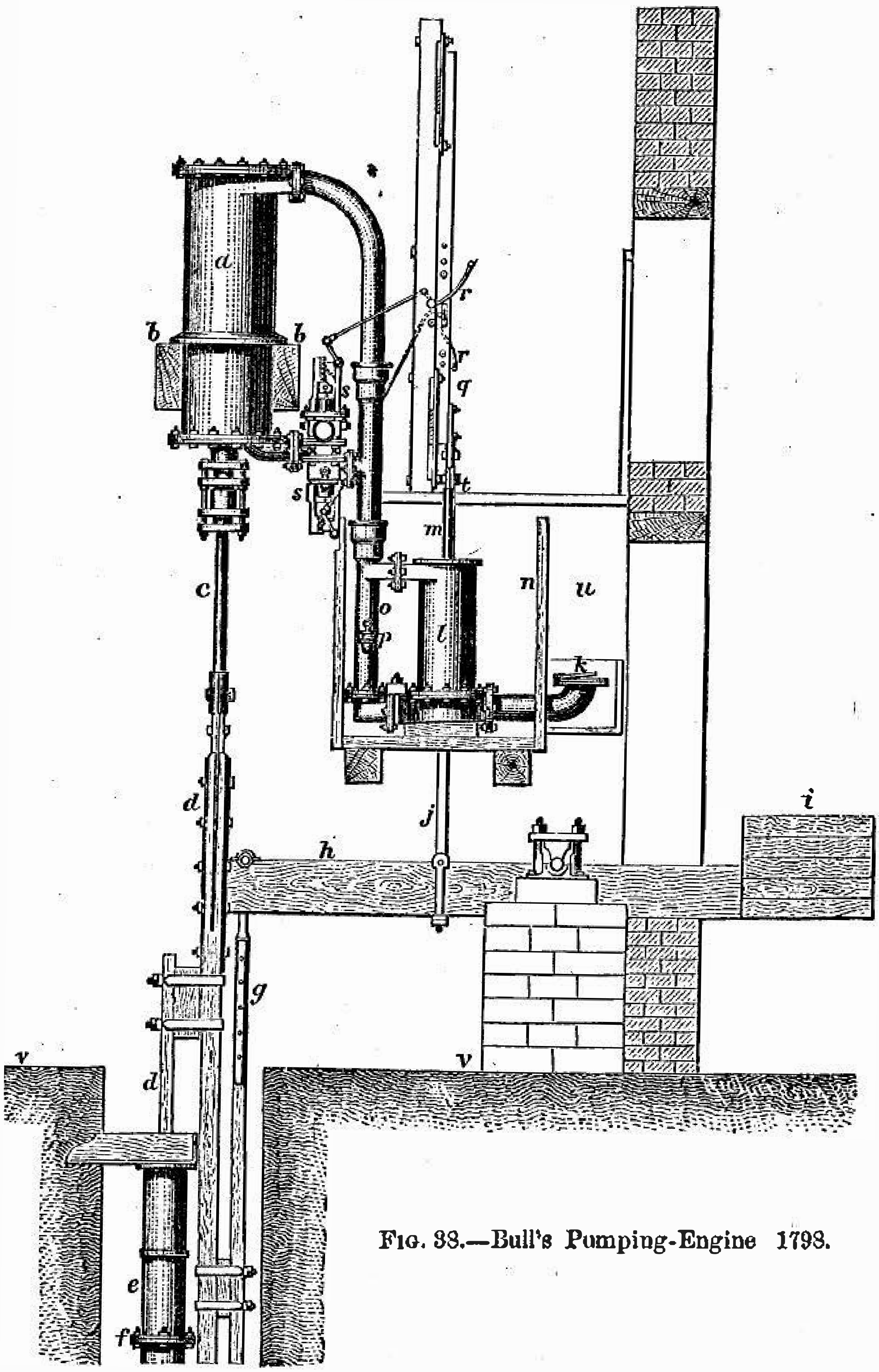


Fig. 33.—Bull's Pumping-Engine 1793.

solid air-pump piston, the valves of the pump being placed on either side at the base, instead of in the pump-bucket, as in Watt's engines. The condensing-water cistern was a wooden tank, *n*. A jet "pipe-condenser," *o*, was used instead of a jet condenser of the form adopted by other makers, and was supplied with water through the cock, *p*. The plug-rod, *q*, as it rises and falls with the pump-rods and balance-beam, operates the "gear-handles," *r r*, and opens and closes the valves, *s s*, at the required points in the stroke. The attendant works these valves by hand, in starting, from the floor, *t*. The operation of the engine is similar to that of a Watt engine. It is still in use, with a few modifications and improvements, and is a very economical and durable machine. It has not been as generally adopted, however, as it would probably have been had not the legal proscription of Watt's patents so seriously interfered with its introduction. Its simplicity and lightness are decided advantages, and its designers are entitled to great credit for their boldness and ingenuity, as displayed in their application of the minor devices which distinguish the engine. The design is probably to be credited to Bull originally; but Trevithick built some of these engines, and is supposed to have greatly improved them while working with Edward Bull, the son of the inventor, William Bull. One of these engines was erected by them at the Herland Mine, Cornwall, in 1798, which had a steam-cylinder 60 inches in diameter, and was built on the plan just described.

Another of the contemporaries of James Watt was a clergyman, EDWARD CARTWRIGHT, the distinguished inventor of the power-loom, and of the first machine ever used in combing wool, who revived Watt's plan of surface-condensation in a somewhat modified form. Watt had made a "pipe-condenser," similar in plan to those now often used, but had simply immersed it in a tank of water, instead of in a constantly-flowing stream. Cartwright proposed to use two concentric cylinders or spheres, betweene which the steam entered when exhausted from the cylinder of the engine, and was condensed by contact with the metal surfaces. Cold water within the smaller and surrounding the exterior vessel kept the metal cold, and absorbed the heat discharged by the condensing vapor.

Cartwright's engine is best described in the *Philosophical Magazine* of June, 1798, from which the accompanying sketch is copied.

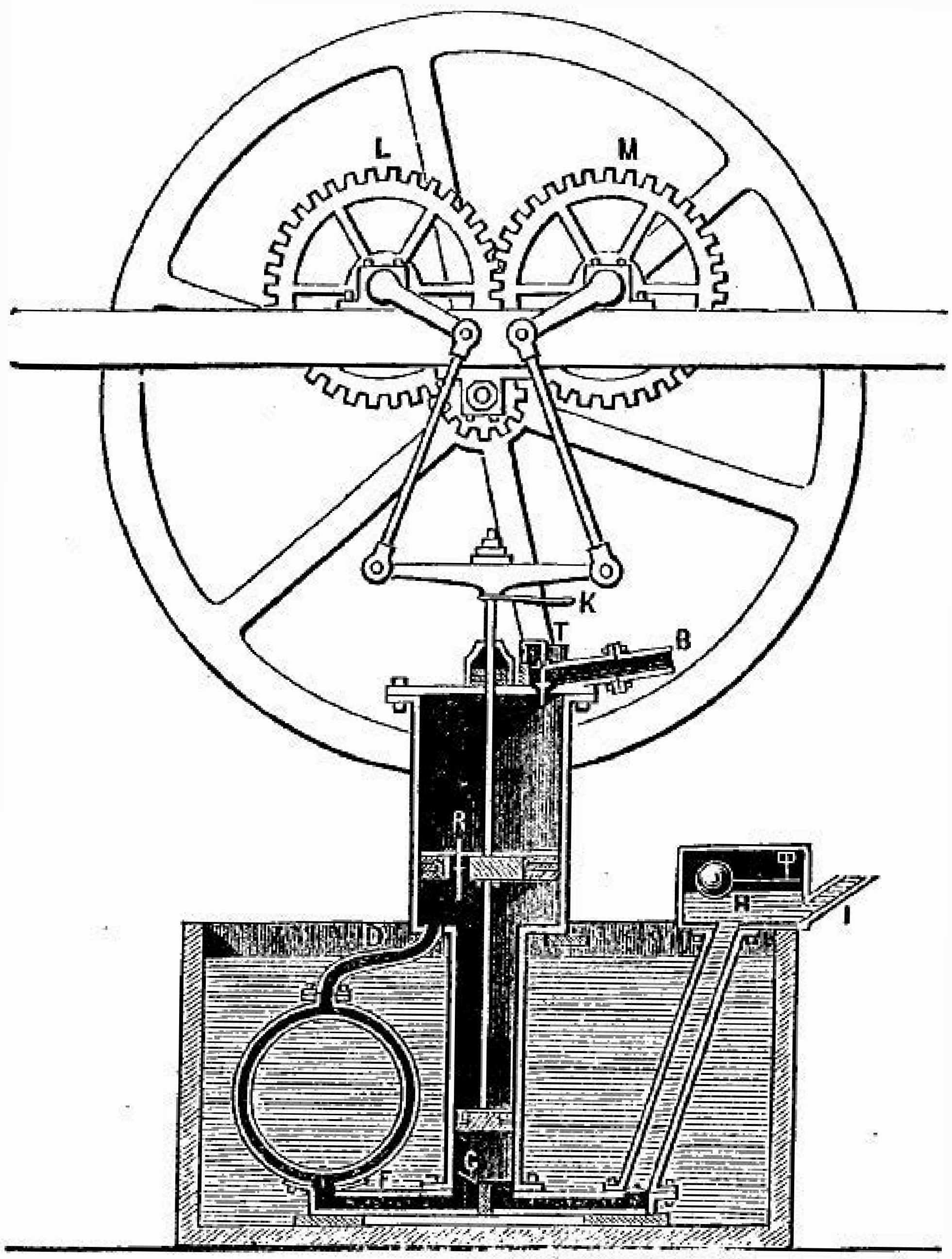


FIG. 89.—Cartwright's Engine, 1798.

The object of the inventor is stated to have been to remedy the defects of the Watt engine—imperfect vacuum, friction, and complication.

In the figure, the steam-cylinder takes steam through the pipe, *B*. The piston, *R*, has a rod extending downward to the smaller pump-piston, *G*, and upward to the cross-head, which, in turn, drives the cranks above, by means of connecting-rods. The shafts thus turned are connected by a pair of gears, *M L*, of which one drives a pinion on the shaft of the fly-wheel. *D* is the exhaust-pipe leading to the condenser, *F*; and the pump, *G*, removes the air and water of condensation, forcing it into the hot-well, *H*, whence it is returned to the boiler through the pipe, *I*. A float in *H* adjusts an air-valve, so as to keep a supply of air in the chamber, to serve as a cushion and to make an air-chamber of the reservoir, and permits the excess to escape. The large tank contains the water supplied for condensing the steam.

The piston, *R*, is made of metal, and is packed with two sets of cut metal rings, forced out against the sides of the cylinder by steel springs, the rings being cut at three points in the circumference, and kept in place by the springs. The arrangement of the two cranks, with their shafts and gears, is intended to supersede Watt's plan for securing a perfectly rectilinear movement of the head of the piston-rod, without friction.

In the accounts given of this engine, great stress is laid upon the supposed important advantage here offered, by the introduction of the surface-condenser, of permitting the employment of a working-fluid other than steam—as, for example, alcohol, which is too valuable to be lost. It was proposed to use the engine in connection with a still, and thus to effect great economy by making the fuel do double duty. The only part of the plan which proved both novel and valuable was the metallic packing and piston, which has not yet been superseded. The engine itself never came into use.

At this point, the history of the steam-engine becomes the story of its applications in several different directions, the most important of which are the raising of water—which had hitherto been its only application—the locomotive-engine, the driving of mill-machinery, and steam-navigation.

Here we take leave of James Watt and of his contemporaries, of the former of whom a French author[1] says: "The part which he played in the mechanical applications of the power of steam can only be compared to that of Newton in astronomy and of Shakespeare in poetry." Since the time of Watt, improvements have been made principally in matters of mereedetail, and in the extension of the range of application of the steam-engine.[2]

[1] Bataille, "Traité des Machines à Vapeur," Paris, 1847.

[2] See "Stationary Engines for Electric Lighting," New York, 1884, "Manual of Steam-Engines," New York, 1890, by the author, for more formal discussion.