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The Search for 'Uniform and Equable Motion': a study of the early methods of the control of the steam engine

by

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Contents

Abbreviations

B & W Colln: Boulton and Watt Collection, Birmingham Reference Library.

T.N.S.: Transactions of the Newcomen Society.

Mayr; O.F.C.: The Origins of Feedback Control.

Dickinson: S.H.S.E.: Short History of the Steam Engine.

Boulton papers: Boulton papers, Assay Office Library, Birmingham.

B.P.: British Patents.

Figures

1. Introduction

"Soon shall thy arm, UNCONQUER'D STEAM! afar
Drag the slow barge, or drive the rapid car;
Or on wide-waving wings expanded bear
The flying-chariot through the fields of air."

(E. Darwin, Botanic Garden, Vol.I, p.29-30, lines 289-292.)

During the 18th century the steam engine - 'the philosophical engine'[1] of the late 17th century - became a reality. The scientific-philosophical experiments and speculations of Della Porta, Robert Boyle, Denis Papin, Salomon de Caus, David Ramsay and Edward Somerset (the second Marquis of Worcester) were given economic and industrial importance, first by Savery who in 1702 set up a workshop for the production of his engines and gave "... notice to all Proprietors of Mines and Collieries which are incumbered with Water, that they may be furnished with Engines to drain the same, at his Workhouse in Salisbury Court, London..."[2], and secondly and more importantly by Newcomen.

The world in which Newcomen's engine was born was a world in need of pumping engines - engines to clear mines of water, to drain fens, and to supply towns with water raised from the rivers - a world needing power, however crude and irregular. Eighty years later the world was more demanding: power alone was not enough, the demand now was for regular power, for uniform motion - "For the mere purpose of raising water, a single-acting engine is sufficient, and double acting engines are rarely employed; but for giving an uninterrupted motion to mills, a double or continuous action is of the utmost consequence to the regularity of motion"[3]. The steam engine had developed "... by the almost regularly alternate steps of experimental research and practical application"[4] and it continued to develop in this way during the 18th century. The regulation of its power was to come about by the application of a variety of devices which, in the main, formed the 'stock-in-trade' of the millwright's practical solutions to individual problems by practical men. Smeaton, perhaps the most eminent of the millwrights, doubted that the steam engine could directly provide regular and uniform circular motion: "I apprehend that

1. J.D.Bernal: Science in History (Penguin Books), p.505.
2. Post Man, March 19-21, 1702, quoted in H.W.Dickinson, A Short History of the Steam Engine, 1938, p.24.
3. J.Farey: A Treatise on the Steam Engine, Vol.1, 1827, p.427.
4. Clark,G.N.: Science and Social Welfare in the Age of Newton, (1938), p.21.

no motion communicated from the reciprocating beam of a fire engine can ever act perfectly equal and steady in producing a circular motion; like the regular efflux of water in turning a water wheel..."[1]. Boulton and Watt, some years later, had to expend much effort in persuading Smeaton of the advantages of their rotative engines.

This is not to say that the practical men were ignorant of the scientific developments of the period; Desaguliers suggestions that the advances which they made were 'owing to Chance'[2] or that "Mr. Newcomen, Ironmonger and John Calley, Glazier not being either Philosophers ... or Mathematicians very luckily by Accident found what they sought for"[3] are overstatements. Without a knowledge and understanding of the scientific (or in Desagulier's terms 'philosophical') principles, the practical men could not have made progress; the accident with the tin-solder[4] would have remained an accident, its importance unrecognised. Desaguliers was reluctant to accept that the steam engine was at that stage in its development where practical knowledge and experience as well as scientific understanding was needed; knowledge and experience which the scientific world of the universities[5] and the Royal Society were unable to supply.

The engine builders of the period saw the need for regulation but they did not distinguish between open and closed loop systems. Their engines were to be balanced; the counterweight on the beam was to be adjusted according to the load. "If it the piston rises too slow, he the engineman puts iron or other ballast, upon the pump end of the lever; and if it rises too quick, he places these weights on the piston end"[6]. The load was to be kept constant, as was the steam pressure, the amount of injection water, the length of the stroke and the frequency with which the engine made a stroke;

1. J.Smeaton: <u>Reports</u>, Vol.II, 23rd Nov., 1781, p.378.
2. J.T.Desaguliers: A Course of Experimental Philosophy, Vol.II, (1744), p.474.
3. Ibid, p.532. Desaguliers was not altogether scathing about practical men despite his reference to "Plumbers and Mill-Wrights now set up for engineers" (ibid, Vol.II, p.415) and the picture given by H.W.Dickinson and L.T.C.Rolt is on the whole distorted, see A.E.Musson and E.Robinson Science and Technology in the Industrial Revolution (1969) Chap.I for the opposing point of view.
4. The discovery of injection of cold water into the cylinder to cause condensation is attributed to the accidental failure of the tin-solder which had been used to seal a small hole in cylinder casing; see L.T.C.Rolt: Thomas Newcomen: The Prehistory of the Steam Engine, 1963, p.56.
5. Lectures on the steam engine were not introduced at Cambridge until 1776, see Hilken: Engineering at Cambridge (1965), p.36.
6. Farey: op.cit. p.187.

the engine was to run at a predetermined steady-state condition. As late as the 1780's, Watt was still searching for improvements in the methods of maintaining the steady-state, as he explains in the preface to his patent of 1782, "... the powers which the steam exerts being unequal, and the weight of water to be raised, or other work to be done by the engines, being supposed to resist equally throughout the whole length of the stroke, it is necessary to render the whole acting powers equal by other means". This patent covered a variety of methods for equalizing the force produced by the piston at various points in the stroke, the most important being: "MY SIXTH METHOD, piece of mechanism, or contrivance for equalizing the powers of the steam, consists in employing the surplus power of the steam upon the piston in the first parts of its motion, to give a proper rotative or vibratory velocity to a quantity of matter which, retaining that velocity, shall act along with the piston, and assist it in raising the columns of water in the latter part of its motion, when the powers of the steam are defective:..."[1]. This is clearly specifying the use of the flywheel. In an earlier patent, dated October 25th, 1781, Watt had explicity mentioned that a "... flyer or heavy rotative wheel should be applied to them to equalise their motion"[2].

This period of predominantly open loop or equilibrium control was brought to a close in 1788 when the 'stupendous powers' of the steam engine were finally curbed by one "... of Watt's beautiful inventions ... the Governor"[3] which, as Peter Drinkwater of Manchester wrote in 1789, "... is of a nature solely calculated to secure more effectually an equable motion under different degrees of heat from the fire; a property so extremely essential in preparing cotton to work into fine yarn, that I would on no account have you deny the use of this instrument"[4].

1. B.P. 1321, 12th March 1782.
2. B.P. 1306, 26th October 1781.
3. S.Smiles: Lives of the Engineers, The Steam Engine, Boulton and Watt, 1878, p.265.
4. B & W Colln: P.Drinkwater to Boulton & Watt, 1789, Nov.21, quoted in Dickinson & Jenkins, James Watt and the Steam Engine, 1927, p.221.

2. The Pumping Engine

"High on huge axis heav'd, above,
See balanc'd beams unweary'd move!
While pent within the iron womb
Of boiling caldrons, pants for room
Expanded Steam, and shrinks, or swells,
As cold restrains, or heat impels,
And, ready for the vacant space,
Incumbent Air resumes his place,
Depressing with stupendous force
Whate'er resists his downward course.
Pumps moved by rods from ponderous beams
Arrest the unsuspecting streams,
Which soon a sluggish pool would lie;
To spout them foaming to the sky."

John Dalton, Descriptive Poem addressed to two ladies at their return from viewing the mines near Whitehaven, 1755.

The atmospheric steam engine was needed to supply the power to pump water from mines; its task, therefore, was to maintain a constant water level. The engineman was charged with the duty of seeing that this task was fulfilled:

"The principal care of the engine-man must be to keep the engine to a steady and regular motion, so that it may always perform the full length of stroke for which it is intended, and yet never exceed that length so as to strike the catch pins upon the stop springs; the due performance of this duty will require a constant attention to the fire, and to the working gear.

He must so manage the fire, by supplying the fuel, and regulating the damper, as to keep the steam always to the same elasticity without variation; and so must adjust the chocks and pins in the plug 1, [the plug rod] as to allow the engine the requisite dose of steam to enable it to perform its task; but he must allow neither more nor less steam than what is requisite; for all excess will do mischief, and cause the catch pins to strike violent and dangerous blows on the springs; and any deficiency will occasion the length of the stroke to fall short of what it should be, and thereby diminish the useful performance of the engine"[1].

The engineman had a difficult task, and neglect could be disastrous. Smeaton designed an automatic alarm for water level in boilers which if the water fell to a dangerous level would "... make a very great noise, and call the engine-man to his duty, even if he may have fallen asleep"[2]. He (Smeaton)

1. Farey: op.cit. p.361.
2. Smeaton: op.cit. Vol.II, p.350.

was on another occasion the cause, albeit indirectly, of damage to one of Watt's engines, for when visiting the distillery at Stratford-le-Bow to examine the engine "He gave the engineer money to drink and the consequence of that was that ye next day the engine was almost broke to pieces"[1]. It may have been this incident that prompted Boulton, a few days later to write to Watt:

"The great thing in the expansive engine is to prevent the fire-man from playing tricks and knocking its own brains out. Suppose a valve was put into the piston and a perpendicular rod rising up from the bottom of the cylinder, which rod must open ye valve as soon as the piston is descended so low and if you find you want more or less power you may either raise or fall ye rod, but that rod must not be in the power of the stoker"[2]. This mechanism opened the valve in 'good fifteenth century fashion' and it was, at Boulton's[3] instigation, tried out on one of the engines at Soho; but no doubt to Watt it must have appeared a crude and impractical mechanism and no more is heard of it.

2.1 The Newcomen Engine

The engine-man working the early Newcomen engine had an easier job, for when it first appeared it was, as a contemporary writer described it, "... a notable piece of machinery working itself entirely ..."[4]; not only was it self-acting but it was also self-regulating. The frequency of the working strokes of the engine was dependent on the steam pressure in the boiler. The mechanism was described by Desagulier in the following terms:

"They used before [i.e. 1713] to work with a Buoy in the Cylinder [he means 'boiler'] inclos'd in a Pipe, which Buoy rose when the Steam was strong, and open'd the Injection, and made a Stroke; thereby they were capable of only giving six, eight, or ten Strokes in a Minute 'till a Boy, Humphrey Potter, who attended the engine, added (what he call'd Scoggan) a catch that the beam Q [the 'plug rod'] always opened: and then it would go 15 or 16 strokes in a Minute. But being perplexed with Catches and Strings, Mr. Henry Beighton, in an Engine he had built at Newcastle on Tyne in 1718, took them all away, the Beam itself simply supplying all much better."[6]

1. Boulton Papers, Boulton to Watt, 1777 April 20. Quoted in H.W.Dickinson & R.Jenkins; James Watt and the Steam Engine, 1972, p.116.
2. B. & W. Colln.: Letter Books. Boulton to Watt, 1777 May 16. Quoted in Dickinson & Jenkins, op.cit. p.120.
3. Dickinson & Jenkins: op.cit. p.121.
4. W.Stukeley: Itinerarium Curiosum, 1776 (2nd ed.). Quoted in L.T.C. Rolt: Thomas Newcomen, 1963, p.69.
5. Desagulier: op.cit. p.553.

This account is not as muddled as Rolt has suggested[1], for, although Desagulier confuses cylinder and boiler, the rest of the account is plausible and clear, with no confusion between 'buoy' and 'boy': it is the later writers - Stuart, Farey, Lardner, Galloway and Smiles - who, in elaborating the story, have caused the confusion and have attributed the original self-acting mechanism, rather than just the modification, to the ingenuity of Humphrey Potter.

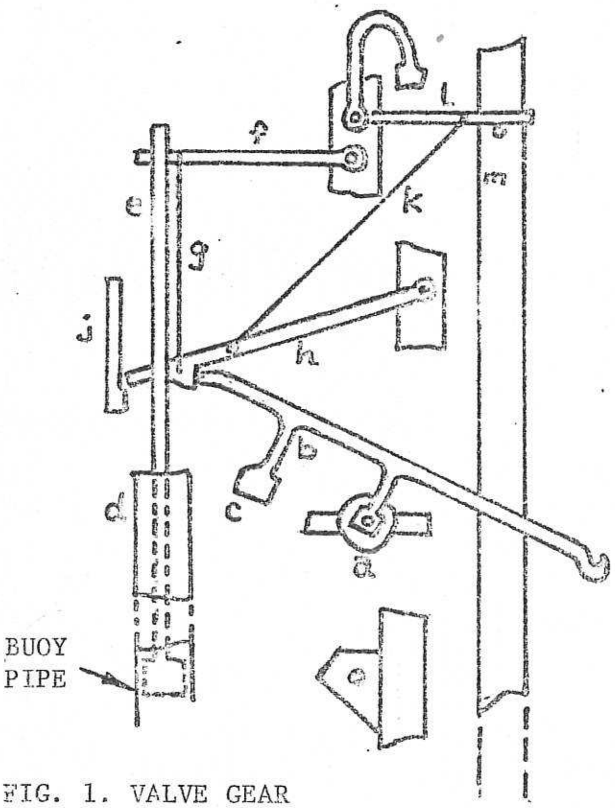


FIG. 1. VALVE GEAR

The 'buoy' referred to above is shown marked d in figure 1; it was a small piston floating upon the surface of the water in the boiler and was enclosed in a vertical tube - the 'buoy pipe'. The action of the buoy was as follows: with the piston 'out of house' (i.e. the piston at the top of the cylinder) and with low pressure in the boiler and cylinder, the detent lever (h) held the lever (b) in its 'up' position, thereby keeping the water injection valve (a) closed. As the pressure in the boiler rose, the buoy rose and at a preset pressure raised the detent lever (h), causing the injection valve to be opened. The influx of cold water condensed the steam, creating a vacuum, the atmospheric pressure on the upper side of the piston forced the piston down and the engine made a working stroke. The pressure in the boiler immediately dropped, and the buoy descended, returning the detent lever (h) to its original position; the descent of the plug rod (m) raised the lever (b) closing the injection valve. The piston was drawn out of house by the counterweight and the cycle repeated.

The original Newcomen engine fitted with a buoy was, therefore, a self-acting mechanism which operated at a predetermined steam pressure and at a stroke rate which could be varied by adjusting the rate of firing of the boiler (since the draught was not controllable). The system was a sequence controller, with a sensor/actuator - the buoy - to start the sequence at the

1. Rolt: op.cit. p.104.

appropriate boiler pressure, and to prevent the engine working at a faster rate than the boiler could support. An engine fitted with a buoy working against a steady load and adjusted for the load must have operated in a steady, regular manner with an even length of stroke, since with operation at constant steam pressure the effects of variation in firing rate of the boiler would have been limited to altering the number of strokes per minute made by the engine. Unfortunately, operation of the mechanism relied on the engine being under-boilered and the pressure being reduced below a critical value on each stroke of the engine. If the steam pressure was not reduced sufficiently, the detent lever (h) was not able to descend sufficiently to hold lever (b) and a continual injection of water would occur, bringing the engine to a stop. Under these conditions the buoy would have had to be wedged down and the engine worked by hand; circumstances which, no doubt, led Humphrey Potter to disconnect the buoy and attach the detent lever to the plug rod.

Desaguliers is not explicit on the date of Potter's invention: it must have occurred before 1717, however, as both the buoy and the 'Potter cord' appear on the engine engraved by Beighton (1717) as they do on the later engravings of Barney (1719) and Triewald (1734)[1]. He is, though, explicit on the date, 1718, of Beighton's discarding of the buoy.

That Newcomen could produce, in 1712, such a well-behaved and well-regulated steam engine excited wonder at the time and has continued to do so. As we have seen, Desagulier expressed disbelief that a provincial could have achieved what Papin and Savery had failed to achieve, and concluded that it must be 'owing to chance'. Some sixty years later, Robison, more charitably, claimed that Newcomen had been in communication with Hooke, and through Hooke had become aware of the experiments of Papin[2]. Dickinson was unable to find any documents in the Royal Society archives to support Robison's claim and concluded that if Newcomen did know of Papin's work it was through the Philosophical Transactions,[3] but that "even this is to suppose that an ironmonger in a provincial town knew of what was going on in the scientific world of London"[3]. Modern opinion[4] is less certain that Newcomen was unaware of the activities in the scientific world; for living and working

1. Rolt: op.cit. p.105.
2. Rolt: op.cit. p.49.
3. Dickinson: op.cit. p.33.
4. see J.Needham: The Pre-natal History of the Steam Engine, Trans. Newcomen Society, Vol.35, p.10, and A.E.Musson and E.Robinson: Science and Technology in the Industrial Revolution, 1969, p.47.

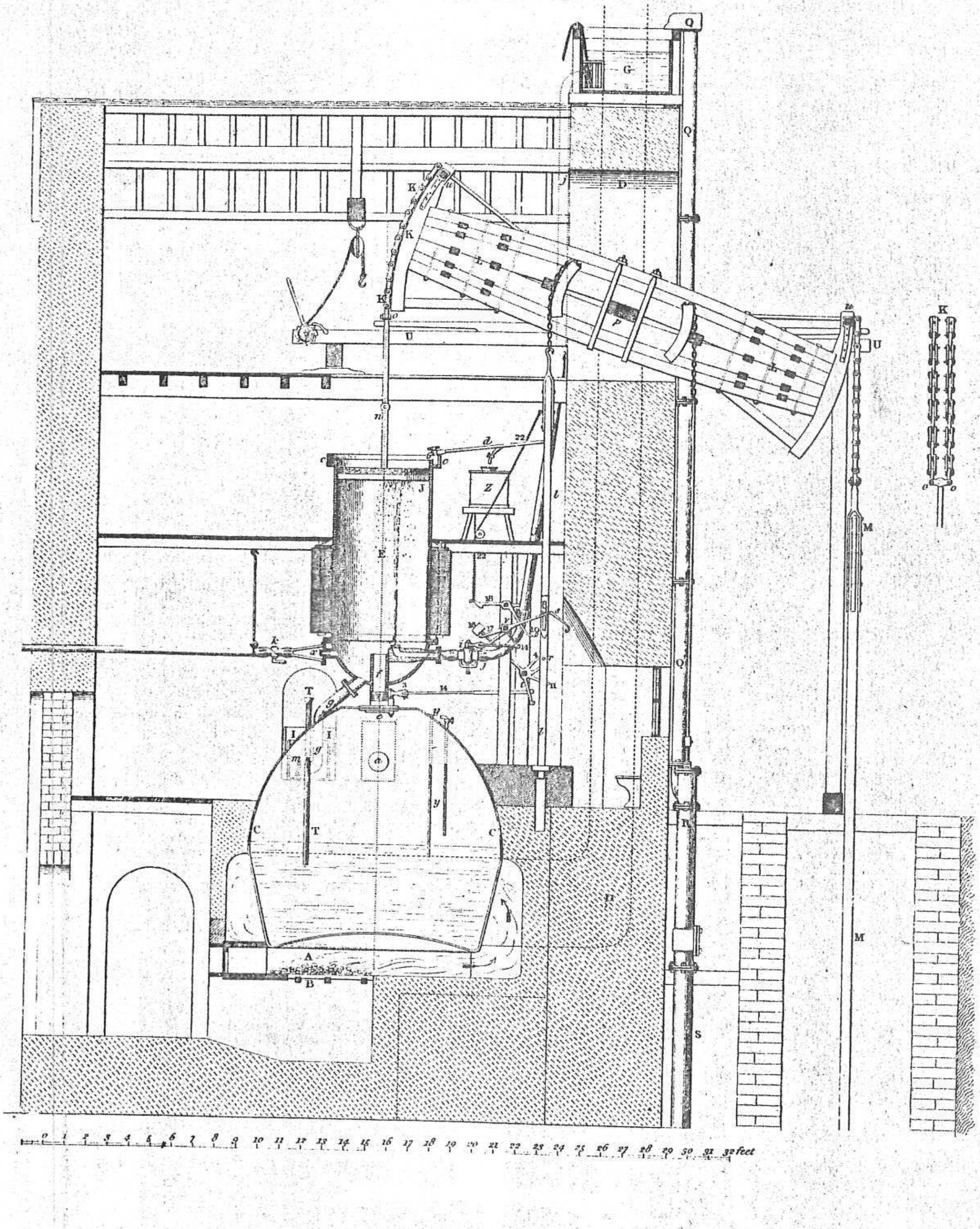


FIG. 2. ATMOSPHERIC ENGINE, SMEATON, 1772.

close to a tin mining area and the mines being in continual danger of being drowned, rumours of the fire engine would have almost certainly have reached him. Having once become involved with the fire engine it would have been natural to attempt to obtain as much information as possible concerning the work of Savery, Papin and others. (See Appendix).

2.2 The Common or Atmospheric Engine

The Common or Atmospheric steam engine at the peak of its development is shown in figure 2, and a block diagram of its operation is shown in figure 3. With the piston 'out of house' (i.e. at the top of the cylinder) as shown, the water injection cock is open, allowing a jet of cold water to enter the cylinder, which condenses the steam thus creating a vacuum in the cylinder. The top of the piston is open to the atmosphere and the pressure difference across it causes the piston to descend and the pump rods to rise. As the piston approaches the bottom of the cylinder the water injection valve is closed and the regulator valve connecting the boiler to the cylinder is opened. The piston continues to move down but is now decelerated by the action of the load on the pump, and by the increase in pressure in the cylinder. During this deceleration period the condensate and injection water are forced out of the cylinder. Once the piston begins to move 'out of house' the pump load is reduced as the non-return valves act to support

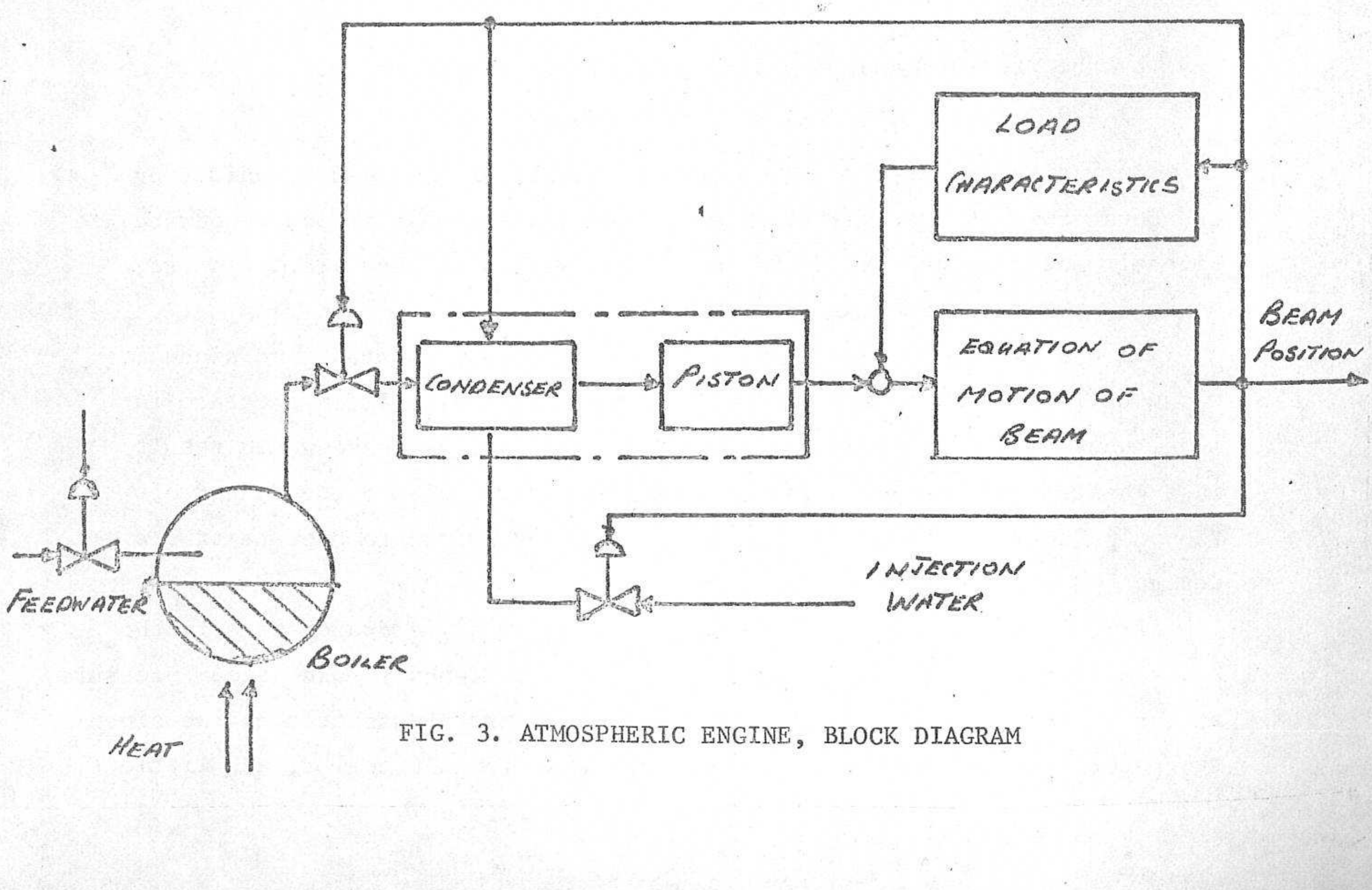


FIG. 3. ATMOSPHERIC ENGINE, BLOCK DIAGRAM

the column of water; the piston therefore returns to the top of the cylinder at a speed determined by the balance of the beam, which is adjusted to give a slight preponderance to the pump end. As the piston approaches the top, the steam regulator is closed, shortly afterwards the injection cock is opened and the cycle repeats.

The power output (or duty) of the engine is proportional to the product of the load, the number of strokes per unit time and the length of stroke; it can obviously be regulated for a constant load by varying either or both the stroke frequency and stroke length. The time and the length of the working stroke, depend on:

a) the load
b) the degree of vacuum obtained in the cylinder (this is in turn dependent on the pressure and quantity of steam supplied from the boiler, the rate of flow of the injection water, and the temperature of the injection water)
c) the duration of the injection in terms of the position of piston when the injection begins and ends
d) the admission and cut-off points for the supply of steam to the cylinder, once again in terms of piston position.

The duration of the returning stroke is dependent on:

a) the balance of the beam
b) the pressure and rate of supply of steam from the boiler
c) the cut-off point for the steam supply.

During the commissioning of the engine, it was trimmed by adjusting the counterweight i.e. the balance of the beam, so that it would operate smoothly and regularly with the load that existed at the time. In use, however, two main problems arose:

i) the influx of water into the mine was never constant and since it was usually desirable to maintain a constant water level (an increase in level would lead to a danger of flooding, whilst a decrease would result in a change of load on the engine, and eventually lead to the danger of the pumps drawing air), the engine was rarely required to operate at its design speed

ii) the firing of the boiler and the supply of feedwater were in the hands of the engine-man and hence there was a tendency for the steam pressure to vary. This was not critical with the ordinary atmospheric engine since the returning piston tended to draw the steam from the boiler, and little attention was paid to controlling the pressure until the engine began to be worked expansively.

The engineman therefore needed to be able to alter the duty of the engine; he could obviously do this in a number of ways, as listed under i) and ii) above, but not all of them were practical. For example the performance of the non-expansive engine is relatively insensitive to the boiler steam pressure, providing that the boiler can supply sufficient steam; the danger and difficulty of using boiler pressure to vary the power output is that if the boiler is not able to supply sufficient steam the engine will slow down and eventually stop with the water injection valve open. Similar problems arise if water injection rate is varied. Therefore attempts were made to fix these quantities and to allow the engine-man to vary, (a) the stroke length by changing the position of the pegs in the plug rod, which operate the valves, and (b) the stroke frequency by holding off the opening of the water injection cock for a time after the piston has reached the top of the cylinder.

In the case of the pumping engine the engine-man was firmly part of the control loop: he was assisted by the provision of safety devices, e.g. the boiler safety valve, catch springs; warning devices, audible and visual; and by the use of open and closed loop regulating devices to maintain constant some engine variables thus easing his task. The methods provided to assist him in this task are discussed below.

2.3 Load Regulation

The lower end of the pump in the mine was enlarged to form a bulb, which was perforated with $1\frac{1}{2}$" diameter holes, 'snore holes'.

Should the water level fall so that these holes were uncovered the load would not suddenly be removed from the engine since the small holes presented some resistance to the ingress of the air and slowly reduced the load on the engine as they were uncovered.[1] The engine-man was also warned that the water was dropping since the sucking in of air produced a 'deafening snoring' and he could make the necessary adjustments to the engine. The full load on the engine could be restored by blocking the holes with wooden pegs or, as on some systems, by a leather skirt attached to the pump pipe[2] - as the water

1. Farey: p.218.
2. ibid: p.219.

level dropped it was turned down to block off the holes and keep the load constant (probably slightly increasing since there would be fewer holes left for the water to enter).

2.4 Water Level Indicators

On some engines the engine-man was provided with information about the water level by means of a float enclosed by the bottom of the pump pipe (see figure 4) and attached to a cord which ran up into the engine house; "... by snatching the weight at the end of the line, in the same manner as a bell-wire is pulled, the engine-man could easily feel whether the float was aground or afloat ..."[1]. The engine-man could then adjust the engine according to the water level.

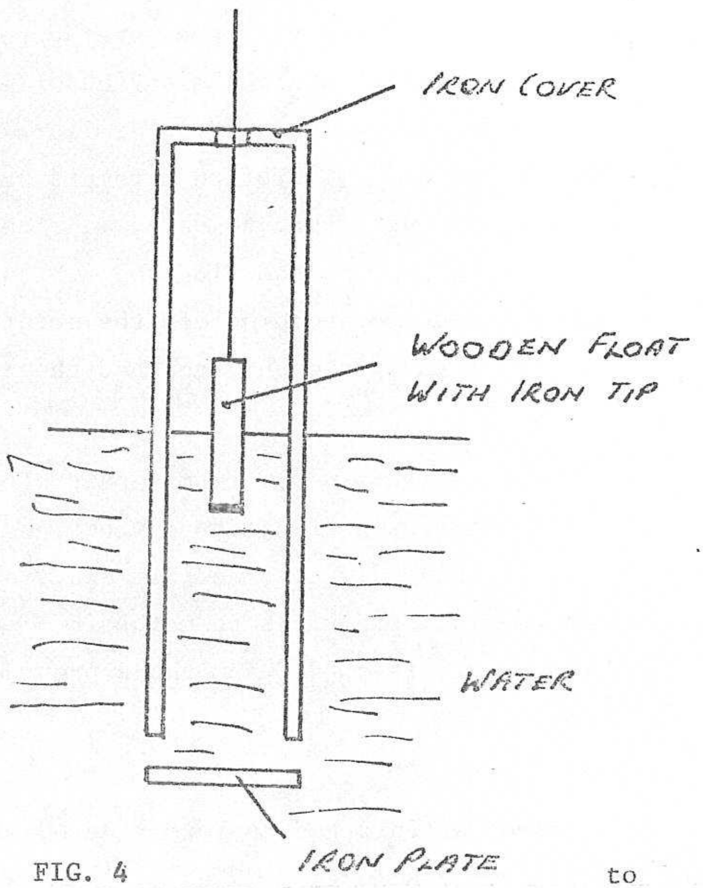
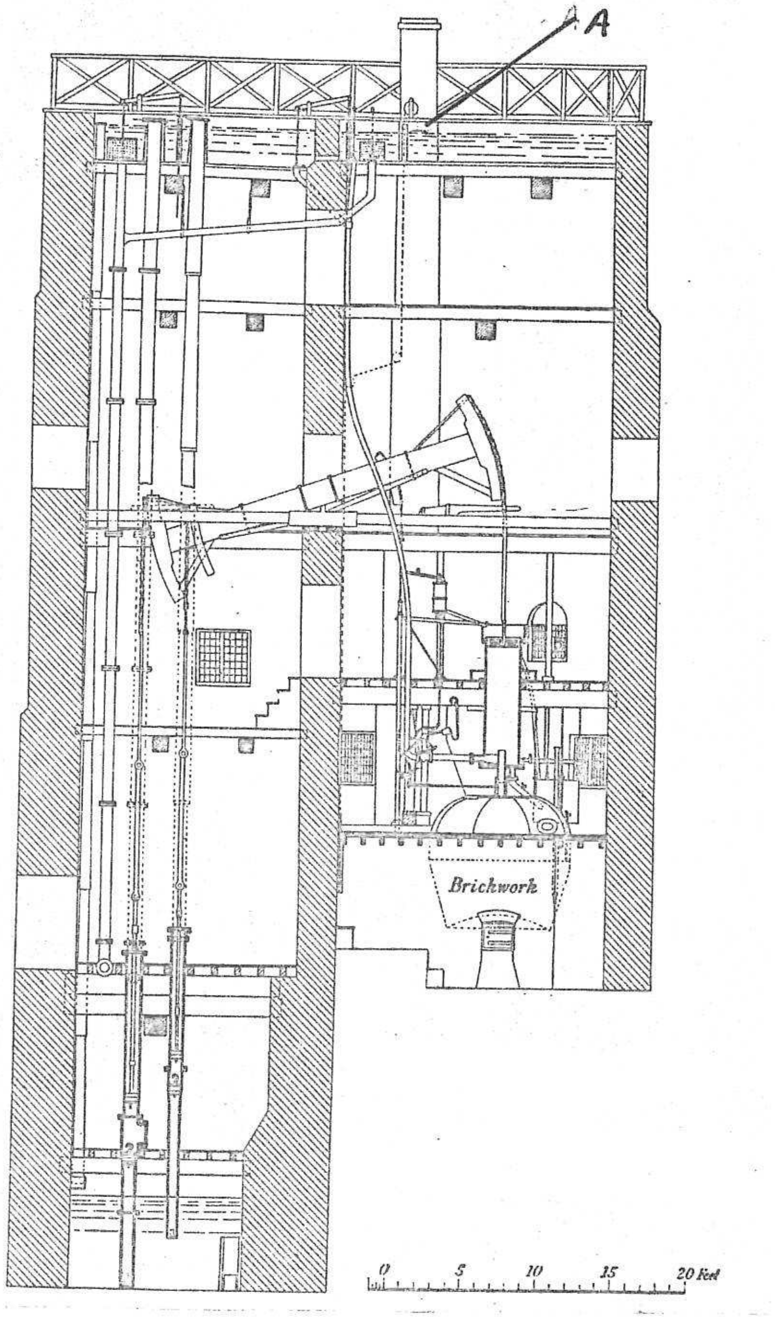


FIG. 4

Another device of this nature was a simple float as shown marked A (Fig. 5) on the drawing of Smeaton's engine for supplying the town of York with water. Attached to the float is a chain which is carried down to the boiler room and hence provides an indication to the engine-man of the reservoir level.

Farey suggested as an alternative to a cataract regulator,[2] that a float with a 'strong copper wire instead of a cord' could be used. "... the end of this wire is connected with the catches of the expansion and exhausting handles, in such a manner as to cause the engines to make a stroke whenever there is sufficient accumulation of water in the pit to supply the pumps; for the float then rises up and disengages the catches, and the engine makes its stroke. In this way the motion of the engine always adapts itself very exactly to the quantity of water which is to be drained, without regard to time".[3] To have produced a mechanical linkage capable of operating the

1. Farey: op.cit. p.224.
2. see page 19 below.
3. Farey: op.cit. p.365.



SMEATON'S PUMPING ENGINE, YORK, 1784. FIG. 5

catches of the engine with sufficient reliability would have been a formidable task and it is highly unlikely that it was ever undertaken. It is also surprising that Farey, writing as he was in the 1820's, should propose a device which tried directly to control the stroke frequency; it might be expected since by this time Watt's automatic damper must have been well known, that he would suggest linking the copper wire to the flue damper or to a throttle valve, hence controlling the steam pressure. Instead of a proportional feedback mechanism then, Farey had proposed yet another form of sequence controller for the pumping engine, and one which was much inferior to the cataract since, because of the low sensitivity of the float mechanism, the engine would have run in bursts rather than at a steady rate.

2.5 Engine Stroke Length

Because of the lack of a fixed constraint on the length of the stroke of the engine, there was the danger that in the event of the sudden removal of the load, the piston would crash through the bottom of the cylinder. To protect against this disaster, the engines were fitted with catch springs which prevented the piston from hitting the bottom of the cylinder.[1]

During normal working the stroke length was controlled by the engine-man adjusting the position of the pegs in the plug rod which were used for operating the water injection cock and the steam regulator.[2] This, on the atmospheric engine, did not alter the time between closing the regulator and opening the water injection valve and so was not a way of reducing steam consumption by allowing expansive working. It was only on the engines with separate condensors and independently operated admission and exhaust valves that true 'cut-off' regulation could be used.

On some engines he could also vary the quantity of the water injected; by reducing the amount of water injected the degree of vacuum produced was reduced and hence the stroke length was reduced. Normally the flow rate for the injection water was fixed by the use of a constant head tank, a device which was used from the beginning and appears on the earliest drawings of the Newcomen engine.

In 1772 Smeaton introduced the 'petcock': this was a cock attached to the cylinder which could be opened to allow air to enter the cylinder, partially destroying the vacuum and hence reducing the length of the working

1. Catch springs apparently were in use from the first Newcomen engine, all the early illustrations, Beighton (1717), Barney (1719) and Triewald (1734) show them.
2. Farey: op.cit. p.188.

stroke.[1] The engine-man was thereby provided with a simple way of adjusting the length of the stroke.

Watt approached the problem in a different way. In his engines steam was admitted to both sides of the piston, and in 1777, for the Chacewater engine,[2] he introduced a 'top regulator' which controlled the amount of steam admitted above the piston.

"There is a third regulating valve, called the TOP REGULATOR, placed in the cross pipe at the upper end of the perpendicular steam pipe, which serves to proportion the Quantity of steam to be admitted from the boiler, to the load of the engine; so that when the load is less than ten pounds and a half on the inch, the steam in the upper part of the cylinder, which presses on the piston, may be less dense or weaker than the steam in the boiler, and consequently a smaller quantity may be employed to do the work than what is required when the engine is fully loaded".[3]

In this engine steam was admitted above the piston and so increased the force on the piston during the working stroke; the piston on the returning rose under the action of the counterpoise only, both sides of the piston being open to the boiler. This was a neat way of adjusting the power output from the engine.

Attempts to devise rotative steam engines were hindered by the variation in stroke length; the simple expedient of using the crank attached to the beam, to turn a wheel was thought to be impracticable, as Stewart in a paper read to the Royal Society in 1777 pointed out (reported by Farey):

"... in practice he [Stewart] thought it would be impossible from the nature of the motion of the engine, which depends on the force of steam and cannot be ascertained in its length, therefore on the first variation the machine would be either broken in pieces or turned back".[4]

2.6 Engine Stroke Frequency

As we have already discussed in the early Newcomen engines the stroke frequency was governed by the steaming capacity of the boiler. With the removal of the buoy, the rapidity of motion was dependent on the steam pressure and the counterweight which controlled the time of the returning

1. Farey: op.cit. p.170, 188, Rolt: op.cit. p.129.
2. Dickinson & Jenkins: op.cit., p.132 & p.177.
3. Watt - direction for working engine, ibid, p.390.
4. Quoted in Farey: op.cit. p.408. The absence of reference to this paper in the Philosophical Transactions suggests that it was not published.

stroke; and the quantity of the injection water and the load, which controlled the time of the working stroke. The counterweight was usually fixed when the engine was installed and could not be easily adjusted whilst the engine was in motion; changes in steam pressure, since they were limited to a few inches of water, had little effect on the motion unless the counterweight was very accurately adjusted. The main method of control was therefore the amount of injection water introduced into the cylinder, a wasteful method: "... much better regulation of the velocity of the engine can be attained by the use of a cataract, or apparatus usually called by the miners, Jack in the Box".[1]

The earliest reference to the use of the cataract to regulate the steam engine is dated 1744 and is Gensanne's (Fig. 6) mechanism for making the Savery engine self-acting.[2] In automating the Savery engine it also provided means for regulating the frequency of the working strokes. Gensanne's device bears a strong resemblance to the cataract used by Robert Fludd to operate his hydraulic floating piston pump. This pump has been described by Needham as follows:

"The two-way cock which admitted the waste water to the cylinder was automated by an ingenious device in which the cock was attached to a lever with a weight at one end and bearing a small vessel at the other. This vessel filled gradually from an auxillary orifice in the side of the down waste water pipe, and when it descended turned the cock so that the pressure head was cut-off and the waste water in the cylinder could escape. At the lowest point of the vessel's travel a valve in its floor was opened in good fifteenth-century fashion by a suitably placed projecting pin, the water flowed out, the counterweight restored the vessel to its previous position, and with the corresponding turn of the cock the cycle recommenced."[3]

It is most unlikely that Gensanne's cataract mechanism was ever widely used, if used at all (it may, however, have provided Boulton with the idea for his mechanism for controlling the power of the engine as discussed above). The common form of cataract was the tipping bucket mechanism, extensively used by the medieval Arab clock-builders and well known in the 17th century.[4]

1. Farey: op.cit. p.188.
2. J.Needham: "The Prenatal History of the Steam Engine", T.N.S. Vol.35 (1962-3) p.13f. Also R.Stuart: Historical and Descriptive Anecdotes of Steam Engines and their Inventors and Improvers, (1829) Vol.1, p.199. Needham suggests that Gensanne's design was also similar to one by Leonardo.
3. J.Needham: The Pre-Natal History of the Steam Engine, T.N.S. Vol.35, 1962, p.5.
4. See Mayr: O.F.C. pp.110-111 for cataract and Chap.III for details of water clocks.

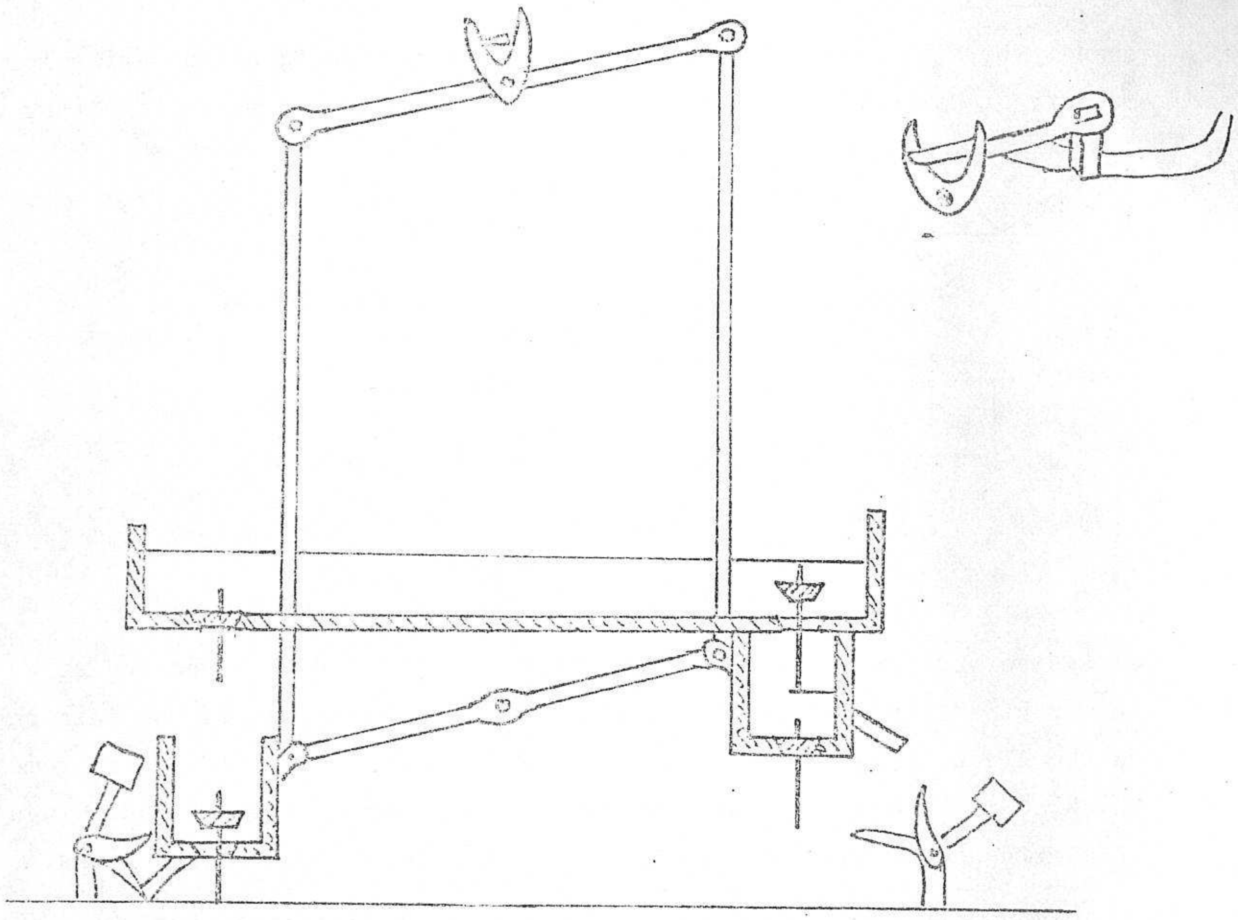


FIG. 6. GENSANNE'S CATARACT

The date of its introduction on pumping engines is, however, difficult to establish; Stower's[1] suggests 1767 as the date of its adoption by Smeaton, whilst Farey[2] simply says that it was widely used in 'Mr. Smeaton's time'. However, it is not until the 1780's that the cataract is mentioned in Smeaton's reports,[3] well towards the end of his working life (he died at the age of 68 in 1792).

The device was apparently well established in Cornwall when Boulton and Watt began erecting engines there, and Watt writing to Boulton in 1777 says: "The cataracts are very good things, and as I shall have experience of one here, shall advise you how they answer".[4] They must have answered well for in another letter of the same year,[5] Boulton suggests the trial of a cataract on an engine at Soho.

As we might expect, the use of the cataract by the firm of Boulton and Watt, resulted in the rapid development of new designs. The earliest of

1. A.J.Stowers: "The Development of the Atmospheric Engine after Newcomen's Death", T.N.S. Vol.35, 1962-3, p.91.
2. Farey: op.cit. p.188.
3. Smeaton: op.cit. Vol.II, p.343f report of 1785.
4. B & W Colln., Watt to Boulton, 1777 Aug. 30. Quoted in Dickinson & Jenkins, op.cit.
5. Ibid, Boulton to Watt, 1777 (not fully dated). Dickinson & Jenkins;

these, shown in figure 7 appeared in 1779 on a drawing of an engine for M. Jary of Nantes.[1] In the same year a cataract, for which 'the same water

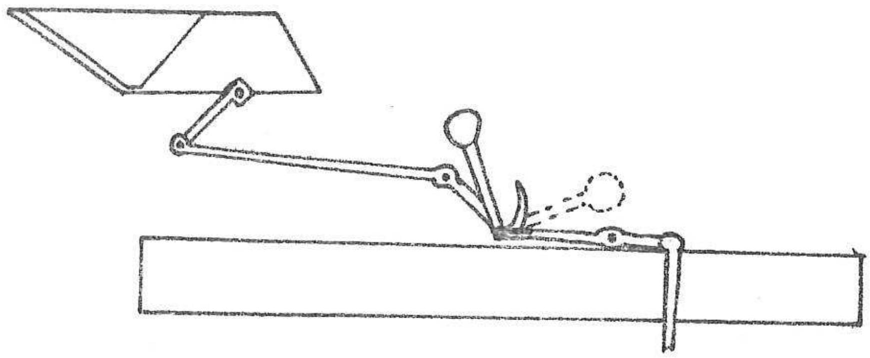


FIG. 7. BOULTON & WATT CATARACT FOR M. JARY'S ENGINE, 1779

always serves for it and is never changed' was tried on an engine at Bedworth.[2] Development continued with the introduction of the 'air cataract' on the Ale & Cakes engine in 1780,[3] and a piston and cylinder arrangement, which seems to have been used at some later stage, although no drawings of this arrangement have been found in the Boulton and Watt collections.[4]

Smeaton in his usual thorough manner investigated the performance of an engine worked (a) with a cataract and (b) self-working with periods of total stoppage. He found that when worked with a cataract the common engine had a lower duty, due to the loss of heat from the cylinder to the external air, since the motion was held with the cylinder full of steam. He concluded, however, that had the periods of total stoppage between the 'self-working' periods been longer, the results of the trial would have been in favour of the cataract, owing to the difficulties and losses in damping down the furnace for long periods: he therefore recommended the use of the cataract.[5]

In 1785, for the Wheal Towan and Wheal Crane engines Boulton and Watt introduced another form of stroke frequency regulator, described as 'an air or water regulating pump similar to those of the cataracts'.[6]

1. see Dickinson & Jenkins: op.cit. plate LIII.
2. B & W Colln.: Boulton to Watt, 1779 Jan.6. Quoted in Dickinson & Jenkins, p.183.
3. Dickinson & Jenkins: op.cit. p.183.
4. Ibid: p.184.
5. Farey: op.cit. p.169 and Smeaton: op.cit. vol.II p.343-345 1785, York Water Works Engine.
6. Dickinson & Jenkins: op.cit. p.184.

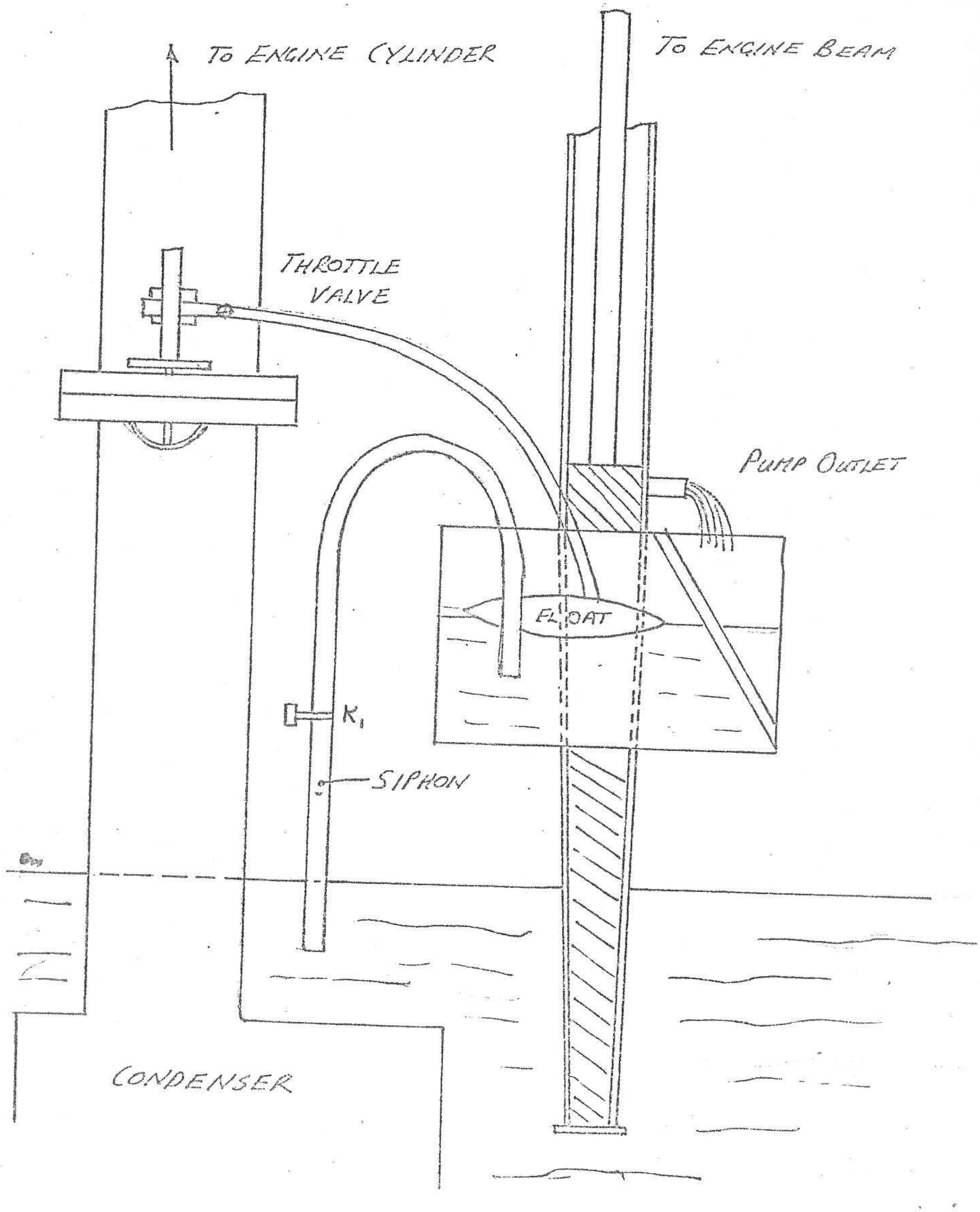


FIG. 8. PERIER'S PUMP REGULATOR

The actual form of this regulator is not known; it may have been similar to the regulator attributed to the Perier brothers[1] or to the system described in Rees Cyclopaedia of 1819.[2] In view of J-C Perier's frequent visits to England (his visit in 1784 was his sixth)[3], and the fact that many of the parts for his engine were made at Soho, it is not unlikely that the regulator attributed to him was a B & W invention.

The mechanism of this regulator is shown in figure 8;[4] the pump driven from the engine beam injects a small quantity of water into the reservoir with each stroke of the engine - this is the speed sensing mechanism. (Note that a splash plate appears to be provided to prevent the incoming water from causing unnecessary movement of the float). The float in the reservoir fulfils two purposes: it supports the siphon which returns the water from the small reservoir to the main condensing tank (maintaining a constant depth of immersion and hence constant flow rate for the return water) and it forms the actuator which operates the throttle valve controlling the exhaust from the cylinder. The regulator is therefore a closed loop feedback system as shown in figure 9.

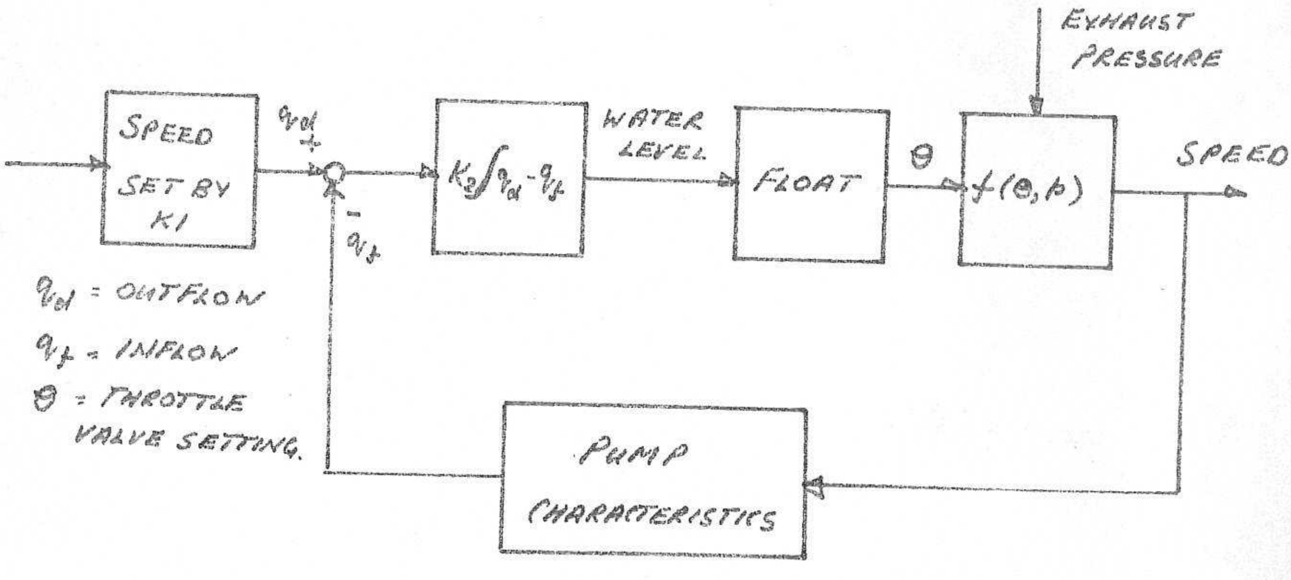


FIG. 9. PERIER'S REGULATOR - BLOCK DIAGRAM

1. Mayr: O.F.C. p.115.
2. A.Rees: The Cyclopaedia or Universal Dictionary of Arts, Sciences and Literature, 1819, entry under Regulator.
3. E.Robinson: Technology and Culture, Vol.12, 1971, Book review, p.639.
4. See Mayr: O.F.C. for a contemporary illustration, p.116.

The major feature of the mechanism is that it provides not simply proportional action but proportional + integral; since the height of the water in the small reservoir is related to the inflow q_{in} and outflow q_{out} by the following expression:

$$q_{in} - q_{out} = \frac{dh}{dt} \times A$$

or

$$h = \frac{1}{A}\int(q_{in} - q_{out})dt + C$$

where A is the cross-sectional area of the reservoir and the constant C is the average water level at the design speed. It would be wrong to assume that the regulator was deliberately designed to have integral action - this feature is simply a consequence of using a float valve. In this device the integral action is an unnecessary complication which results in poorer dynamic characteristics; any offset due to proportional action alone can be easily adjusted for by means of the stop cock on the siphon.

A regulator of this form was used in 1785 for the Wheal Towan engine, this being the first recorded attempt at applying feedback control to the overall speed/load loop of the steam engine. Although it provided a reasonably satisfactory solution for the regulation of the beam engine, it was sluggish, had low sensitivity and a tendency to break down.[1] With the introduction of the fly-ball governor some three years later, it was discarded as a method of speed control.

2.7 Boiler Control

In the Newcomen engine fitted with a 'buoy' the engine made a stroke each time the steam pressure reached the preset value, and hence the whole engine could be viewed as a (highly inaccurate) pressure controller. Once the 'buoy' was dispensed with, there was nothing to prevent the pressure in the boiler rising to dangerous levels. As a consequence a safety valve was introduced to limit the maximum steam pressure. The safety valve, as Mayr has pointed out, was accepted as a 'conventional machine element' as early as 1717-1718.[2]

1. T.Tredgold: Steam Engine: Its Invention and its Progressive Improvement, (1827), vol.1, p.264.
2. Mayr: op.cit. p.82.

The lever safety valve first appeared on Papin's pressure cooker in 1681 and its invention is unanimously attributed to him.[1] Its first appearance on a steam engine was on Papin's engine of 1707[2] and it was adopted by Beighton, on the suggestion of Desaguliers,[3] and appears on the 1717 engraving. The device remained virtually unchanged from its introduction until Murray's spring load safety valve of 1820.[4]

No other device for regulating steam pressure appears to have been used until about 1775-1779 when the flue damper was introduced. The date of its introduction cannot be placed exactly: Farey[5] says that they were not used in 'Mr. Smeaton's time', whilst in Watt's book Directions for erecting and working the newly-invented steam engines written in 1779 we find Watt writing "When the fire is newly made, the damper should ..."[6] and a manually operated damper can be seen on a drawing of a double-acting rotative engine for Cotes and Jarratt (dated June 1784).[7] The late introduction of the flue damper is not surprising since until steam began to be used expansively the actual steam pressure exerted little influence on the engine performance.

The flue damper was a well known device, Holmyard has suggested that it was first introduced in the 15th century by a Bristol chemist, Thomas Norton.[8] In "The Ordinall of Alchemy", Norton claims that he has invented a new all purpose furnace:

> "Three score degrees divers ye maie gett,
> For threescore warkes, and everie-ech of divers Heate,
> Within the Furnace, to serve your desire,
> And all thi served with one litle Fier,
> Which of a Foote square onlie shalbe".

He goes on to say how this shall be done:

> "Consider your Stoples, and lerne well this,
> The more is the Stople the lesse is the Heate,
> By manifould Stoples Degrees ye maie gett."[9]

Published shortly after Norton's poem was a description of Drebbel's 'athanor'.[10]

1. Mayr: op.cit. pp.82-83 - see also p.84 for block diagram of pressure regulator.
2. F.Klemm: A history of Western Technology, 1959, p.226.
3. Rolt, p.106.
4. Dickinson: S.H.S.E. plate X.
5. Farey: op.cit. p.146.
6. Boulton and Watt: Direction for etc., 1779, section LXV.
7. Reproduced in Dickinson and Jenkins: op.cit. p.394. ibid, plate XXXV, p.164.
8. E.J.Holmyard: Alchemy, 1957, p.46.
9. "The Ordinall of Alchemy" was first published in a Latin translation in 1618, the original english version was not published until 1652, see Holmyard p.189. The extract is quoted in Holmyard, op.cit., p.197.
10. Cambridge University Library, Manuscript No. 2206.

This is a temperature controlled oven and can be dated as prior to 1624[1]; the regulator of the oven uses a vessel filled with alcohol to sense the temperature, the expansion or contraction or which causes a column of mercury to rise or fall; the movement of the mercury operates a damper, forming a closed loop temperature regulation system.

The 17th and 18th centuries saw many temperature regulators designed and built, but from the point of view of the control of the steam engine, William Henry's "Sentinel Register"[2] is the most interesting. The temperature sensor of the Sentinel shows great similarities to Boulton and Watt's pressure sensor as used on his automatic boiler damper mechanism. In the Sentinel the temperature is sensed by the expansion of air (see figure 10), this causes the water level in the vessel to rise, and the rising of the float operates the flue damper through a linkage system. In Boulton and Watt's device the steam pressure causes the water level to rise, raising the float and hence operating the flue damper. Henry supposedly met Watt whilst on a business trip to Britain.[3] We do not know whether the Sentinel was discussed on this occasion. Watt may well have heard of the device from one of his many visitors, such as Benjamin Franklin, or from other members of the Lunar Society, since being a temperature regulator it may well have come to Josiah Wedgewood's notice. It is probable that Watt knew of the device, but did not consider its use necessary, since at the boiler pressures then used, variation in pressure had little effect on the duty of engine. It may have been the patents of 1799 granted to Robert Delap on April 6th[4], and to Mathew Murray on July 16th[5], of that year which prompted the firm of Boulton and Watt to examine the need for automatic control of steam pressure. (The

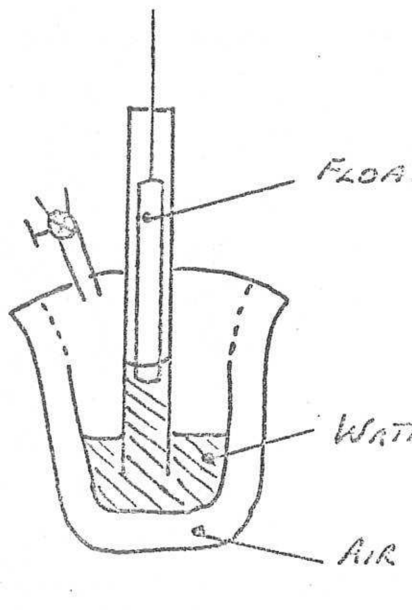


FIG. 10. WILLIAM HENRY'S SENTINEL REGISTER

1. Mayr: O.F.C., p.55.
2. See Mayr: O.F.C. Chap.VI for details of this and other temperature regulators.
3. Mayr: O.F.C., p.69.
4. B.P. No.2302, 6th April 1799: Robert Delap, "Boilers for Steam Engines, etc."
5. B.P. No.2327, 16th July 1799: Matthew Murray, "Steam Engines".

automatic flue damper was introduced about the time of Watt's retirement from the firm[1] and its development must be attributed to the firm and not to Watt himself).

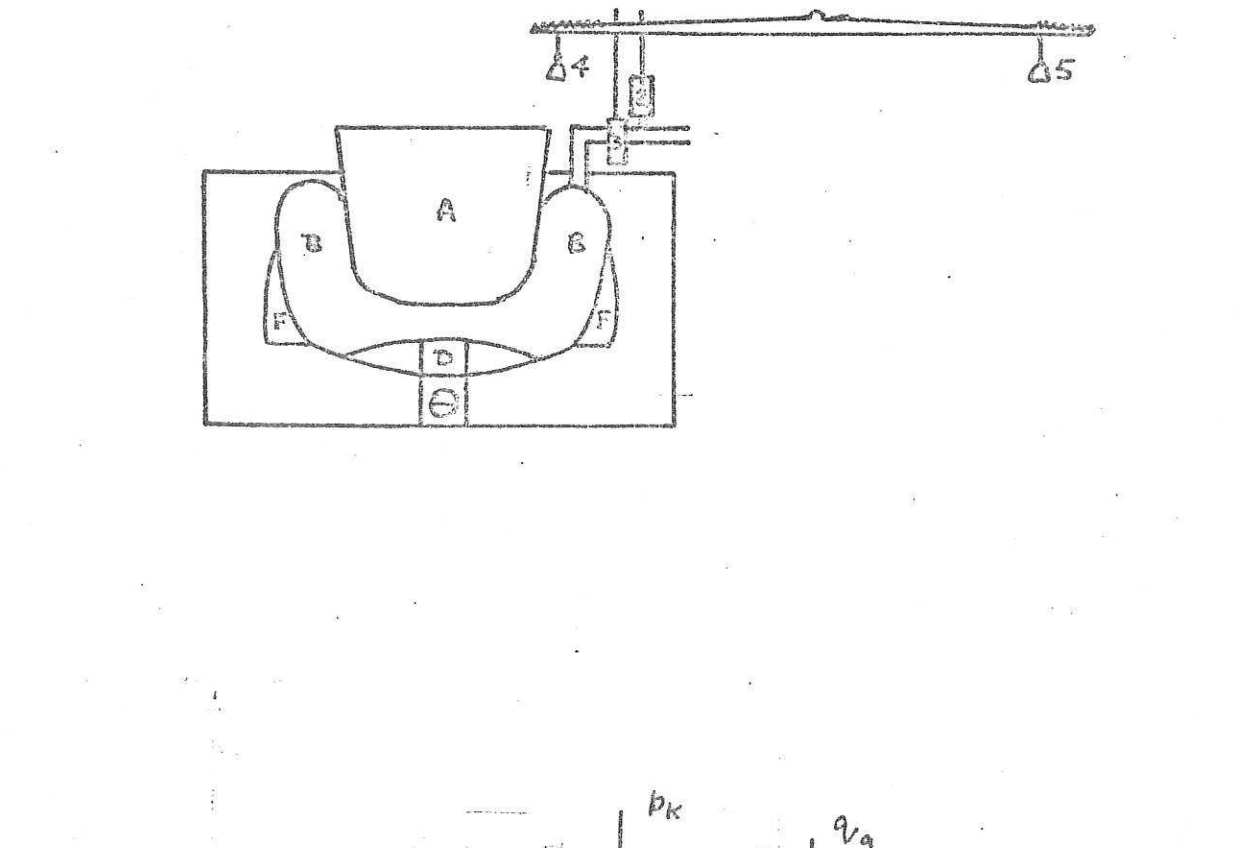
Delap's pressure regulator (figure 11) is an adaptation of the lever safety valve; the pressure sensing piston (2) is located on the engine side of a throttle valve (3), a change in pressure causes this piston to rise or fall and hence through the lever opens or closes the throttle valve. The desired engine pressure is set by adjusting the weights on the lever; the pressure can be set either to be above or to be below atmospheric pressure. The system as specified provides only on-off control. A spring or other means of increasing the force on the piston (2) as the pressure increased is necessary to give proportional action; without proportional action, because of the small time constant of the system, it would have been unstable.

It is unlikely that this form of regulator was ever used. It was aimed at the control of pumping engines working with constant load, but by 1800 attention was turning to the use of the governor and to load-sensitive controllers, which could cope with varying loads.

The regulator of Matthew Murray worked on much sounder principles and operated not by throttling the steam to reduce the pressure but by using the pressure of the steam to adjust the flue damper position. The regulator is shown in figure 12. The piston in the boiler is used for sensing the pressure and is connected to a rack, which meshes with the pinion mounted on an axle, attached to the damper plate in the flue; as the pressure increases the piston rises and rotates the damper, hence reducing the air-flow through the flue. The crucial part of the mechanism is the small spiral cam attached to the axle. As the piston rises the cam rotates and the increased moment arm of the weight hanging from it increases the torque opposing the movement of the piston; there is, therefore, proportional action. The desired working pressure can be set by adjusting the size of the weight attached to the cam.

Although this device represents an improvement on Delap's regulator it suffers from the defects that the piston would need to be a good fit in the cylinder, leading to considerable friction, and this would introduce unpredictable errors in the pressure measurement.

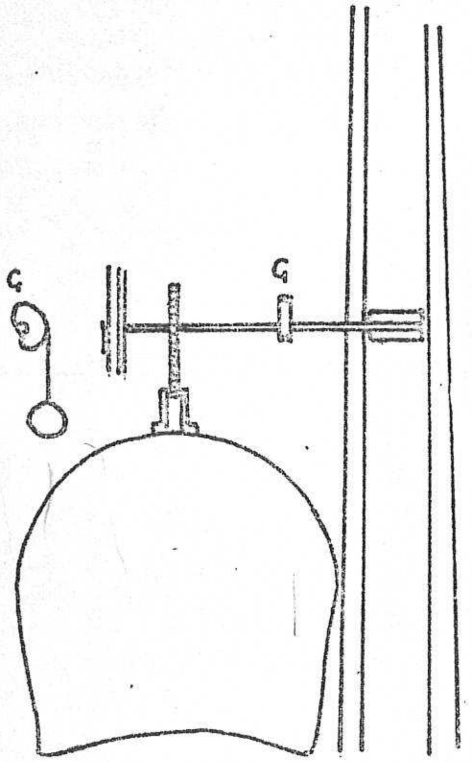
1. Farey: op.cit., p.695.



r = desired pressure load on piston
p = actual pressure
b = force on piston
e = s - b

s = valve opening
p_k = boiler pressure
q = flow rate of steam

FIG. 11. DELAP'S REGULATOR



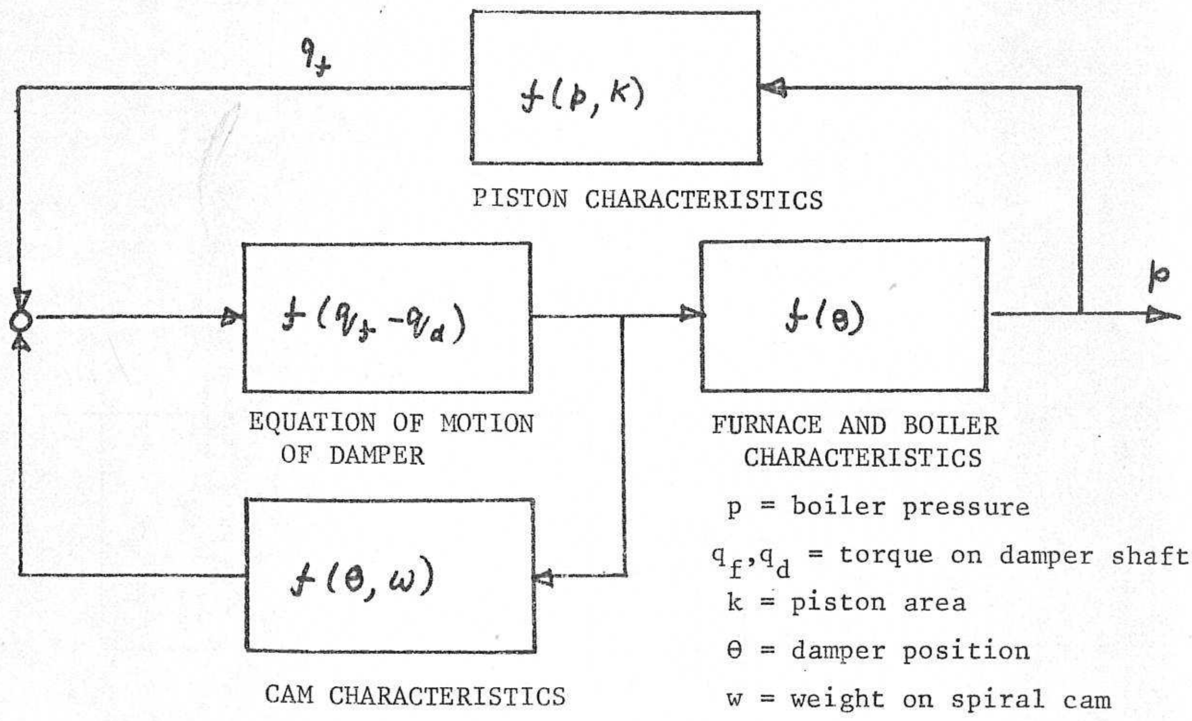


FIG. 12. MURRAY'S PRESSURE REGULATOR

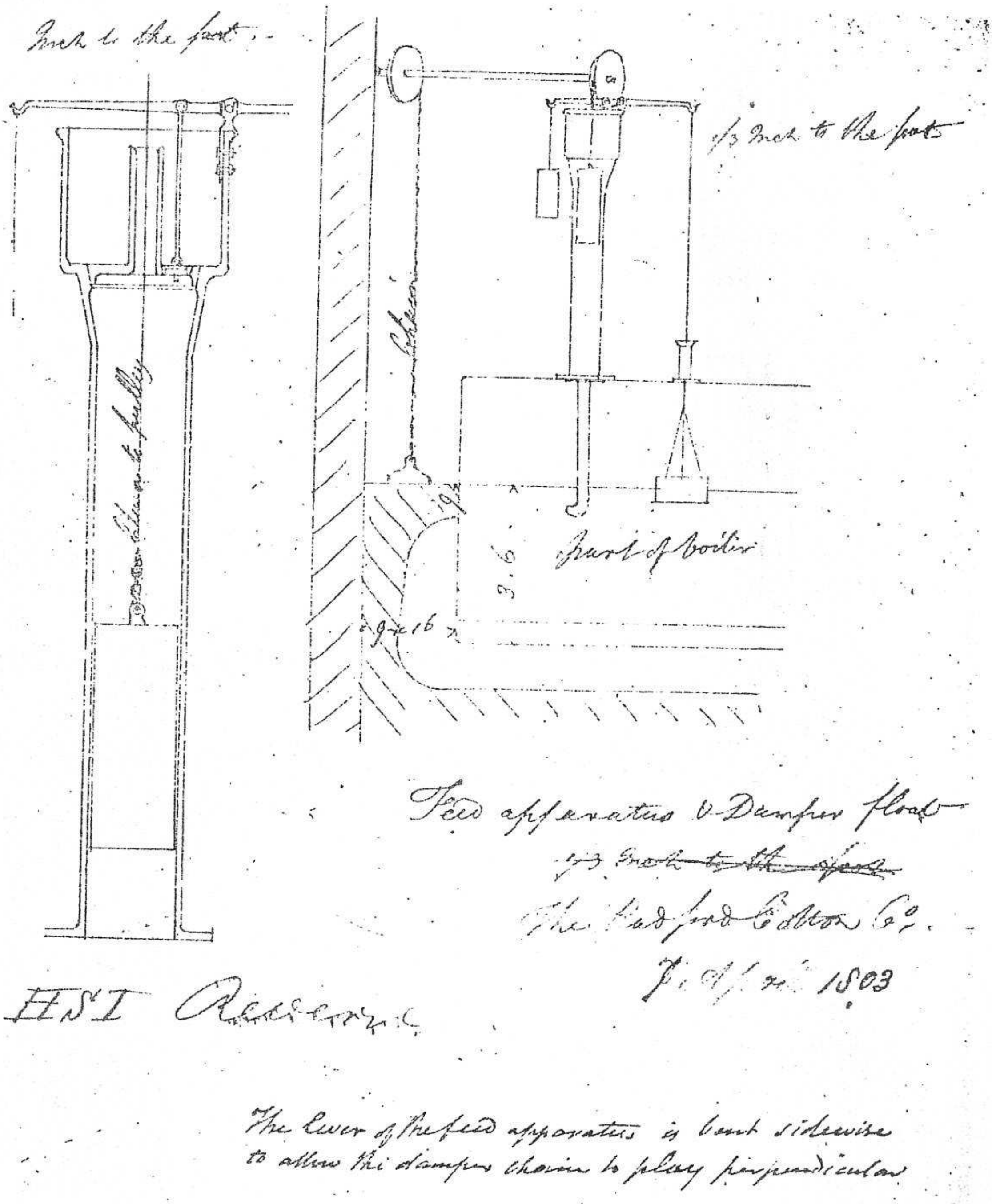
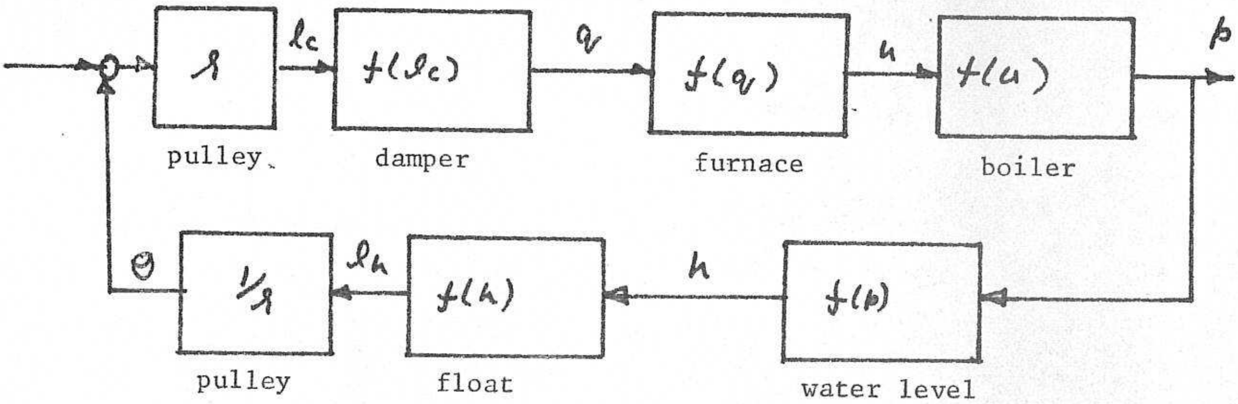


FIG. 13. BOULTON & WATT DAMPER AND AUTOMATIC BOILER FEED APPARATUS

The pressure regulator of Boulton & Watt (see figures 13 and 14) works like Murray's regulator by varying the position of the flue damper; the major difference lies in the method used for sensing the steam pressure. In the Boulton & Watt regulator the boiler pressure forces a column of water up a vertical pipe (Watt's engines worked with a steam pressure of only a few lbf/in^2). The float inside the tube is connected to the damper by a pulley and chain mechanism, and as it moves with the water level it operates the damper: the desired pressure could be set by adjusting the length of the chain. This simple and practical control system seems to have been widely used.[1]



ℓ_c = damper chain length

ℓ_u = float chain length

θ = pulley angular position

q = air flow

u = heat output from furnace

p = boiler pressure

h = water level

FIG. 14. BOULTON & WATT DAMPER - BLOCK DIAGRAM

An interesting feature of Boulton & Watt Co's self-regulating damper introduced between 1784 and 1791[2] is that it also incorporates an automatic feed-water mechanism. A float valve in the boiler is used to open and close a 'clack valve' allowing the feedwater to enter the boiler under gravity. Feedwater regulators had been patented by Brindley[3] in 1758 and Wood[4] in 1784 but do not seem to have been used on steam engines, for Smeaton writing in 1775 says:

"The upright feeding pipe L, pipe into the boiler in the general upright, pl. VI front elevation is here designed to anser, not only the purpose of a lower gage cock, but of a safety pipe, which will be done by

1. Mayr: O.F.C., p.89.
2. Mayr: p.80.
3. B.P. No.730, 27th Sept. 1758, "Fire engine for drawing water out of mines".
4. B.P. No.1447, 20th August 1784. see Mayr: O.F.C. Chap. VII, pp.76-81 for details of Brindley and Wood devices.

boring two or three gimblet holes through it at the depth proper for a lower gage cock, and three inches lower than these holes, to bore a hole of half an inch diameter, and three inches below that to terminate the pipe altogether: by this means, when the water is got to a low, the small holes will give notice by producing a rackling noise; when the steam blows by the half inch hole, the noise will produce greater alarm, and when so low as at intervals to get to the bottom of the pipe, the water and steam will issue in such a manner as to awake the dullest apprehensions".[1]
A foretaste of automatic smoke alarms!

Similarly Watt in engine directions in 1779 and 1784 refers to manual adjustment of feedwater "By a little attention, you will find the proper opening of the feeding cock for any rate of working" (1779)[2], or "The water in the boiler should be kept as nearly of the same height as possible; as carelessness in this point may cause the most sudden destruction of the boiler..." (1784)[3].

Smeaton had also introduced a simple form of preset control for the feedwater supply; he provided two cocks, one of which could be set to maintain the correct feed, the other could be used to turn the feed on or off in the event of a stoppage[4].

Around 1790-1800, at the height of its development, the expansive pumping engine was provided with fully automatic control of boiler water level and steam pressure, and its power output was regulated either by a cataract or by a float regulator. The engineman's duty was now restricted to firing the boiler, adjusting the set point of either the cataract or the float regulator and being prepared either to shorten the stroke or shut down the engine in the event of a sudden reduction in load.

1. Smeaton: Reports Vol.II, p.351 "Chase Water Engine", 14 Feb. 1775.
2. Boulton & Watt: "Directions for erecting and working the newly invented steam engines", Section LXIV (1779), reproduced in Dickinson & Jenkins, op.cit., p.394.
3. Boulton & Watt: "Directions for working rotative engines", C.1784, XX reproduced by Dickinson & Jenkins: op.cit., p.400.
4. Farey: op.cit., p.241.

3. Rotative Engines

"There the vast mill-stone with inebriate whirl
On trembling floors his forceful fingers twirl
Whose flinty teeth the golden harvests grind,
Feast without blood and nourish human-kind.
. . . .
With iron lips his rapid rollers seize
The lengthening bars, in thin expansion squeeze;
Descending screws with ponderous fly-wheels wound
The tawny plates, the new medallious round;..."

(E. Darwin: Botanic Garden (1791 2nd Ed.), Cant.1, p.27-28, line 275-278 and 281-284).

From Hero's aerophile, through Branca's and later Papin's rowing machines, proposals for the steam engine had always included mechanisms for the production of rotary motion. "I personally almost think that this discovery can be used for many other purposes besides raising water. I have made a little model of a carriage, which is moved forward by the power"[1] wrote Papin in 1698. He proposed using a rack and pinion system; in describing his system for propelling a boat he says: "It would be easy to set axles in motion by means of our tube (cylinder), having the oars fixed at the extremities. It would then only be necessary to furnish the shafts of the pistons with teeth, in order to set in motion small toothed wheels fixed to the axles of the oars"[2].

The alternative to the ratchet mechanisms was the use of the steam engine to raise water, which was then used to turn a water wheel. Savery in his "Miner's Friend" proposed this system[3], which was first used by Champion at Bristol who in 1752 operated several water wheels by water raised by a steam engine[4]. Further systems of this type were installed by Smeaton at Carron Iron Works in 1765[5], by Watt at Broseley in 1776[6], and Stewart's engine at Hartley Colliery, subject of an abortive attempt at directly producing rotative motion, was converted to a pumping engine and used to supply water to drive a water-wheel[7].

1. Papin to Leibniz: 25th July 1698, quoted in Klemm: op.cit., p.223.
2. D. Papin: Fasciculus dissertation uin de novis quivuselam machinis, Marburg, 1695 quoted in Klemm: op.cit., p.222.
3. Farey: op.cit., p.405.
4. ibid: p.212 and p.296; Lardner: The Steam Engine... 7th Ed., LONDON 1840,p.181
5. ibid: p.276.
6. Dickinson & Jenkins: op.cit., p.115.
7. Farey: op.cit., p.297.

This strategy had much to commend it: in the infancy of the steam engine the capacity of the reservoir provided a useful reserve of power in the event of a temporary breakdown of the steam engine, whilst the speed of the water wheel was much more easily regulated than the speed of the steam engine. Smeaton was greatly in favour of this method of working and his improvements in the design of water wheels meant that "... the necessity of employing steam power for mills was not felt until some years afterwards,..."[1]. But when the necessity was felt, Smeaton continued to support the use of water-wheels: "I apprehend that no motion communicated from the reciprocating beam of the fire engine can ever act perfectly equal and steady in producing a circular motion, like the regular efflux of water in turning a water wheel..."[2] This in reply to the Commissioners of the Victualling Office who in 1781 sought his advice concerning a proposal to use Boulton and Watt engines to drive a corn mill[3].

It was important to the firm of Boulton and Watt that the views of Smeaton, at this time considered the leading authority on millwork and steam engines, should not discourage potential purchasers of their rotative engine. Through the auspices of the Lunar society they attempted persuasion[4], at first with little success as Watt reported to Boulton in October 1782: "He [Smeaton] grows old and rather more talkative than he was but retains in perfection his perspicuity of expression and good sense. He came also to the Philosophers meeting at this house on Monday and we were receiving an account of his exp erimen ts on rotatives and some new ones he had made when unluckily his facts did not agree with Dr. Mayes the blind philosopher theories which made Mayes contradict S and brought on a dispute which lost us the information we hoped for,..."[5]

This unproductive meeting was followed by the gift of one of Watt's copying presses (the second to go to Smeaton) and more arguments and demonstrations which were ultimately successful in persuading Smeaton to recommend the rotative engine[6].

1. Farey: op.cit., p.296.
2. Smeaton: Reports, Vol.II, p.378, letter dated 23rd Nov. 1781.
3. It is only fair to point out that Smeaton's main concern was the unreliability of the steam engine, and the difficulty in adjusting it to operate under widely varying load conditions. The arguments about pump storage schemes continue today in the generation of electricity.
4. R.E.Schofield: "<u>The Lunar Society of Birmingham</u>" (1963), p.245.
5. Boulton Colln: Watt to Boulton, 28th Oct. 1782 quoted in Robinson: <u>T.N.S.</u>, vol.35, pp.166-167.
6. Schofield: op.cit., p.246.

The first atmospheric steam to directly produce rotary motion was erected by a Mr. Oxley at Hartley colliery in 1762[1], an engine which Watt described thus:

"The first I knew of the latter kind [rotative motion derived from reciprocating engine], was one I saw at Hartley Colliery about 1768, which consisted of a toothed sector on the end of the working-beam, working into a trundle, which, by means of two pinions with ratchet wheels, produced a rotative motion in the same direction, by both the ascending and descending stroke of the arch... It was employed to draw coals out of a pit, had no fly-wheel, and went sluggishly and irregularly; the name of the inventor I have long since forgotten"[2].

Four years earlier in 1758[3], Keane Fitzgerald had prepared a scheme for a rotative engine which incorporated a fly-wheel[4].

John Stewart in a paper given to the Royal Society in 1777 proposed a rotative engine which could be used for driving flour mills, in which the mill-stone would serve as a flywheel; for saw-mills and the like, some other heavy wheel may be added to form a flywheel[5]. Smeaton replied that although "... a fly-wheel might be applied to regulate the motion, it must be such a large one as would not be readily controlled by the engine itself;" and that "the use of such a fly-wheel would be a greater incumberance to a mill than a water-wheel to be supplied by water pumped up by the engine"[6].

A successfully rotative engine was soon to follow, in 1779. Matthew Wasborough (for James Pickering)[7] erected an engine at Snow Hill fitted with a ratchet and pawl mechanism, which was replaced towards the end of 1780 by a connecting rod and crank[8]. The crucial feature of this engine was, as in later life Watt admitted, that "...Matthew had added a flywheel, which, as far as I know, was the first time that it had been employed for that purpose"[9].

1. Farey: op.cit., p.408, Lardner: op.cit., p.182.
2. Watt to James Watt junr, 10 November 1808, quoted in Muirhead: op.cit., Vol.III, p.37fn.
3. Date given in letter from Sir Joseph Banks to James Watt, Feb. 23 1814, quoted in Muirhead: op.cit., Vol.III, p.345.
4. Farey: op.cit., p.407.
5. Farey: op.cit., p.408.
6. Farey: op.cit., p.409.
7. Dickinson & Jenkins: op.cit., p.149.
8. Dickinson & Jenkins: op.cit., p.150.
9. Muirhead: op.cit., Vol.III, p.37fn.

Watt had been aware of the crank[1], as were all the millwrights and engineers, but was doubtful whether it could be used, doubtless because of the variable length stroke of the engine. He was also aware of the flywheel but, "... was, however, desirous to render the motion equable without a fly-wheel, the regulating power of which I did not then fully appreciate,..."[2].

He had appreciated the need to 'equalize' the force exerted by the piston during its stroke if a rotative-engine was to operate with any regularity, and in his usual thorough way had worked out a number of schemes. These are grouped under six heads in his patent of 1782, and in all amount to 12 schemes.

"MY SIXTH METHOD, piece of mechanism, or contrivance for equalizing the powers of the steam, consists in employing the surplus power of the steam upon the piston in the first parts of its motion, to give a proper rotative or vibratory velocity to a quantity of matter which, retaining that velocity, shall act along with the piston, and assist it in raising the columns of water in the latter part of its motion, when the powers of the steam are defective..."[3].

A flywheel is shown in the drawing and its action is described thus: "When the piston pulls down the end of the working beam, the toothed sector QQ gives motion to the pinion, and thereby gives velocity to the fly; and when the descending or ascending velocity of the arch or sector of the working beam comes to be less than the velocity which the pinion and fly have acquired, then the velocity of the fly continuing, causes the pinion to act upon the sector in its turn, and assist the powers of the steam, until its velocity is spent, or the piston has reached the bottom of the cylinder;..."[4]. This was not altogether a true application of the flywheel in that it was brought to rest at the end of the working stroke and turned in the opposite direction during the returning stroke. But he continues: "In the Second variety of this method, a fly, or heavy wheel, is put into a continued rotative motion by a crank ..."[5]. Also in the previous year, Watt had described the use of the flywheel:

1. See Dickinson & Jenkins: op.cit., p.653 - entry in Journal Dec. 5 1779, or Muirhead Vol.2 letter to Mr. Turnbull, Feb 23rd 1771. Explicitly mentions crank.
2. Muirhead: op.cit., Vol.III, p.37.
3. B.P. 1321 12th March 1782, for full transcription and reproduction of colour wash drawings, see E.Robinson and A.E.Musson: "James Watt and the Steam Revolution", (1969) pp.96-108 and plates 1782.
4. ibid.
5. ibid.

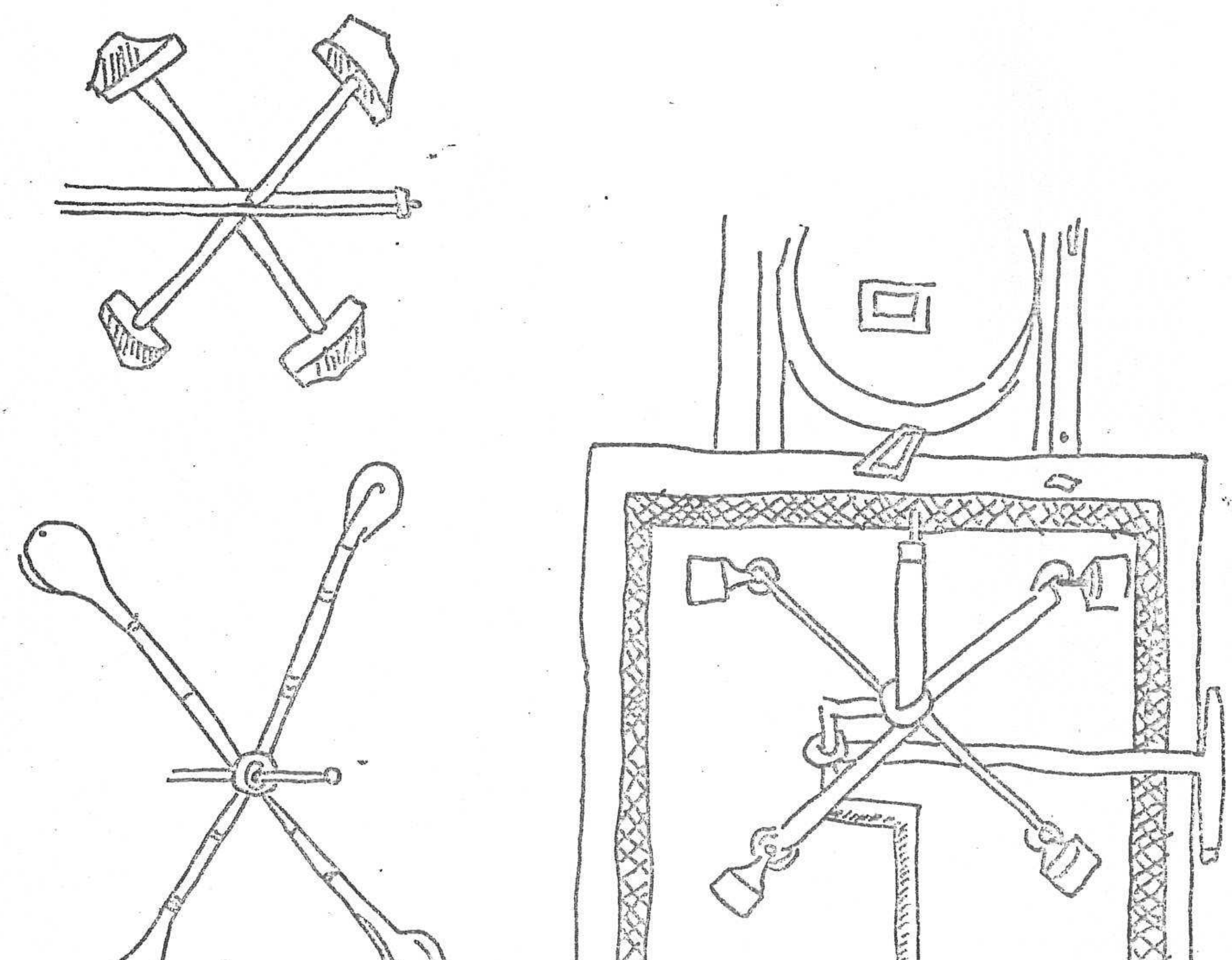


FIG 15. FLYWHEELS FROM HUSSITE MSS

"AND BE IT REMEMBERED, that in all cases where heavy wheels or swift motions are not otherwise necessary to the uses to which any of the four preceding methods herein described may be applied, a flyer or heavy rotative wheel should be applied to them to equalise their motion"[1].

3.1 Energy Storage Devices as Regulators

The use of flywheels to regulate motion was not new: "The most ancient flywheel was presumably the neolithic spinning-wheel, but it did not find great application before the paleolithic period. Another example would be the potters wheel. Second in antiquity would be the heavy discs on bow-drills and pump-drills, attested from so many cultures, as on the ancient Egyptian crank-drill"[2]. The flywheel was even recognised as a separate part of a machine in 12th century[3], and they are illustrated as such in a Hussite manuscript of the first part of the 15th century (see figure 15)[4]. An interesting feature is the variable inertia flywheel, a variation of which appears in a design for a handmill by Francesco di Giorgio shown in figure 16[6].

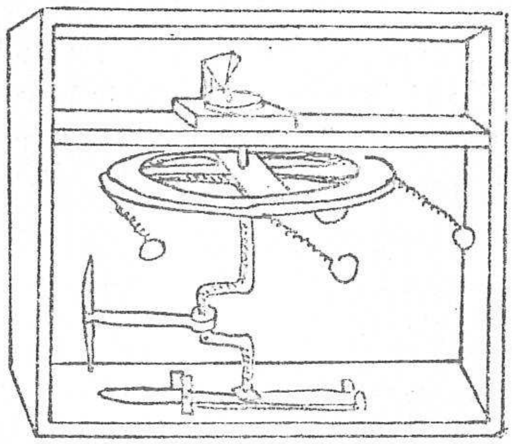


FIG. 16. HANDMILL WITH FLY-WHEEL

Gille in describing this mechanism completely misunderstands the nature of it:

"And there is no doubt that here we have the most astonishing idea of the Sienese F. di Giorgio inventor: the ball governor, which at its final stage of development, was one of the achievements of Watt, three centuries later"[6].

1. B.P. of October 25th 1781.
2. J.Needham: Science and Civilisation in China, Vol.4, Pt.2, section 27, p.91.
3. ibid, p.103 fn. (a).
4. B.Gille: The Renaissance Engineers, English edition, 1966, p.72.
5. ibid, p.111.
6. ibid, p.111.

In the 17th century R. D'Acres in his book "The Art of Water-Drawing" 1659, refers, almost en passant, to the use of a flywheel: "... some little help is added hereunto by addition of a superfluous heavy swey, voluble voluntary wheel, as some call it, which being more in weight than the water, will (being one set a moving) help the work for a little short space; but then it must be answered again, with renewed strength, or else it presently desists"[1]. And again in the early part of the 18th century we find Desagulier saying: "The Fly (b) [the flywheel as illustrated in the drawing which accompanies Desagulier's description seems to be much too small to perform its function] regulates the Motion of the Engine to an equal Velocity; and by its running forwards, after the Buckets are quite up or down, holds them steady till they begin to fill or empty, and prevents their recoiling back"[2].

It is strange therefore, that despite this early recognition of the flywheel, the engine for Hartley Colliery should be built without one. Smeaton was disparaging of Stewart's proposal to use a flywheel[3], but on this occasion was no doubt looking for an excuse to damn Stewart's proposal since the success of such a system might have taken business away from him. On another occasion we find Smeaton actively recommending the use of a flywheel: "The rings of the two water-wheels I have designed to be of cast iron, in order that they may act as loaded flies, and thereby preserve the motion more steady"[4].

As we have seen, some two years after Stewart's proposals, Wasborough's engine had a flywheel and it is reported[5] that after 1780 atmospheric engines used for winding coal were made rotative by means of a crank and flywheel - these were the 'whimseys'. An engine of this type was enthusiastically described by Boulton in 1784 in the following terms: "I never saw an engine take so little steam as this in my life and you may be assured that where a fly can be apply'd so as to go 300 or 400 ft per minute, the expansive principle in practice will come up to theory"[6]. By the end of 1781 Watt[7]

1. R. D'Acres: The Art of Water-Drawing, 1659, reprinted 1930 by W. Heffer & Sons for The Newcomen Society, p.12.
2. Desagulier: op.cit., Vol.II, p.464.
3. See above.
4. Smeaton: op.cit., Vol.I, p.378, extract dated Austhorpe, Oct. 15 1770.
5. Stowers: op.cit., p.87.
6. B & W Colln.: Boulton to Watt, 1784 July 8. Quoted in Dickinson & Jenkins op.cit., p.126.
7. Watt had been 'unwilling to load his engine with a heavy fly' yet as early as 1769 in a letter to Dr. Small say "The power will indeed be unequal, but this can be remedied by a fly, or by several other means" May 1769 quoted by Lardner, p.157.

was convinced of the value of the flywheel and its use is recommended in his patent of October 25 1781[1] and in letters to Boulton in January and February 1782[2] concerning the patent proposals for equalisers he mentions the flywheel; in the February letter he says: "But the flyer is the best of all and will prove the true equaliser, and will have much less friction than any other". And as we have seen, the use of the flywheel formed the sixth method of equalising the motion, in the patent of 1782[3].

Watt, true to his nature, was still cautious. He carried out "... many experiments with the forge-engine, when raising water to ascertain the consumption; and found that with the rotative fly it used about, cwt. 0.735 per hour, at 27½ strokes per minute = cwt. 0.28 for 20 strokes; but, on being freed from the fly and rotative motion, it was only, cwt. 0.235 per hour for 20 strokes per minute. In both cases the boiler evaporated 11 feet per cwt."[4] This was an experiment on the "Soho Small Engine" to determine the losses due to driving the reciprocating mechanism; these losses, would be insignificant compared to the losses which were incurred in the alternative method of obtaining rotative motion to drive tilt hammers, namely the use of a water-wheel supplied with water from a pumping engine. Not that the use of water-wheels was necessarily uneconomic: some 14 years later Curr summed up the position as follows:

"The common machine with a water wheel and engine, have been chiefly built before the third plan of applying its power immediately, was made manageable and useful; and as it does not require more than half the power when the engine alone is applied, and the original expence being little more than one third, we can have no difficulty in condemning the further introduction of the water wheel, excepting where a brook can be conveniently had to do the business"[5].

As the demand for iron increased during the 18th century, the need for 'blowing engines' to supply air for the blast furnaces increased. These engines were typically banks of bellows driven by a water-wheel. The blast

1. B.P. October 25th. 1781.
2. Watt to Boulton 3 Jan. 1782, quoted in Muirhead: op.cit., p.136.
   Watt to Boulton 16 Jan. 1782, quoted in Muirhead: op.cit., p.137.
   Watt to Boulton 14 Feb. 1782, quoted in Muirhead: op.cit., p.143.
3. B.P. March 12th. 1782.
4. Watt to Boulton, 2 Oct. 1783, quoted in Muirhead: op.cit., Vol.II, p.178.
5. J.Curr: The Coal Viewer and Engine Builder's Practical Companion, 1797, p.35. Reprinted by F. Cass & Co. Ltd., 1970.

was maintained uniform by arranging the bellows to blow in sequence[1]. In 1776 work started on the erection of a Watt engine which was to directly drive a cylindrical bellows to provide an air supply for John Wilkinson's New Willey Furnace, near Broseley, Shropshire. A drawing of the blowing apparatus shows that the blast was maintained uniform by means of 'regulating belly' as shown in figure 17.

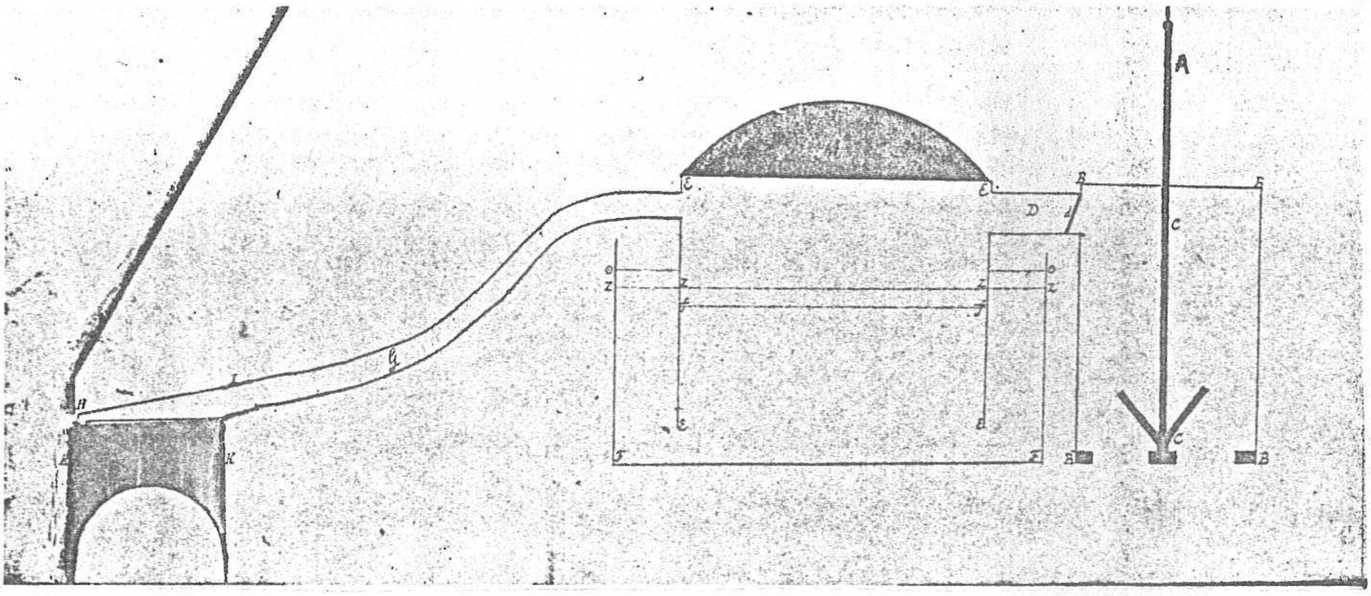


FIG. 17. BROSELEY BLOWING-APPRATUS, 1776
(DICKINSON & JENKINS, Pl CXI)

The inscription on the original drawing reads: "This section is supposed to be made at the instant that the Beam A and the Piston C are at their greatest descent. On their rising again, the valves shut, and the air contained in the blowing cylinder is forced through the pipe D, into the regulating Belly E, and not being discharged by the opening L as fast as it enters at d, the water in the Belly is driven from the dotted line z to f, and in the cistern from z to o - As during the descent of the piston C no air is forced through d, the endeavour of the water to return to its level at z serves effectually to keep up a constant blast at L - "[2].

Dickinson and Jenkins are of the opinion that this blowing cylinder and regulating apparatus were in use with an early engine at Broseley, and that Watt had nothing to do with the design of these parts[3]. This seems to be the earliest recorded use of an accumulator to regulate a blowing engine.

A different form of regulator was in use in 1777 at another blast furnace belonging to Wilkinson, this time at Wilson House, Lancashire; the

1. See for example the description of the blowing engines at Carron Iron Works, Farey: op.cit., pp.270-275. This was a similar solution to that proposed by Papin in his scheme for driving paddle wheels by a steam engine. Lardner: op.cit., p.179.
2. British Museum, Egerton Ms. 1941, ff.5-20, reproduced as Plate XCI in Dickinson & Jenkins: op.cit. opp. p.245.

regulator for this blowing engine consisted of a heavily loaded piston which "... rose and fell, so as to float, as it were, upon the air contained in the cylinder"[1]. The difficulties of sealing a piston sufficiently well to enable this regulator to operate would have been enormous. It also suffered from the same defect as Delap's steam pressure regulator, in that with a constant load on the piston it would tend to rise up against its stops as soon as the air pressure exceeded a set value. A partial remedy to this defect was provided by arranging for the piston to pick up weights slung from an overhead beam as it rose[2].

Accumulators were also used with engines used for supplying water for towns; an air vessel was connected to the delivery pipe of the water pump, (as shown in figure 18), the compressed air in the vessel maintained the pressure on the supply whilst the pump made the return stroke. On the Boulton & Watt engine of 1803, the pressure in the air cylinder was used to provide feedback to control the speed of the engine. Two mechanisms were in use: one was to use the pressure measurement to adjust the throttle valve, the other was to adjust the cut-off point of the admission of steam to the cylinder[3]. The method of measuring the pressure was the simple one of connecting a small pipe to the lower part of the air vessel (below the water level). A piston was fitted in the pipe and had attached to it a heavy chain part of which rested on the floor; as the piston moved up due to an increase in air pressure, additional links of the chain were raised from the floor increasing the load on the piston and thus providing proportional action.

3.2 The Fly-ball Governor

Boulton and Watt began in 1783 an enterprise which, although a technical success, was to lose them £9,000, when it was destroyed in 1791[4]. This was the Albion Mills, near Blackfriars bridge in London, with two steam engines, driving 10 pairs of grindstones each. In one week in June 1790 the sales of flour from the mill amounted to £6800[5] and the operation of the mill reduced the price of flour by 3s 4d a sack[6]. During the period of operation

1. Farey: op.cit., p.328.
2. ibid, p.283.
3. Farey: op.cit., pp.722-723 and plate XXIII.
4. Dickinson & Jenkins: op.cit., p.65. Boulton and Watt had had to put up a large proportion of the capital required for Albion Mills.
5. ibid, p.167.
6. H.W.Dickinson: Matthew Boulton, p.123.

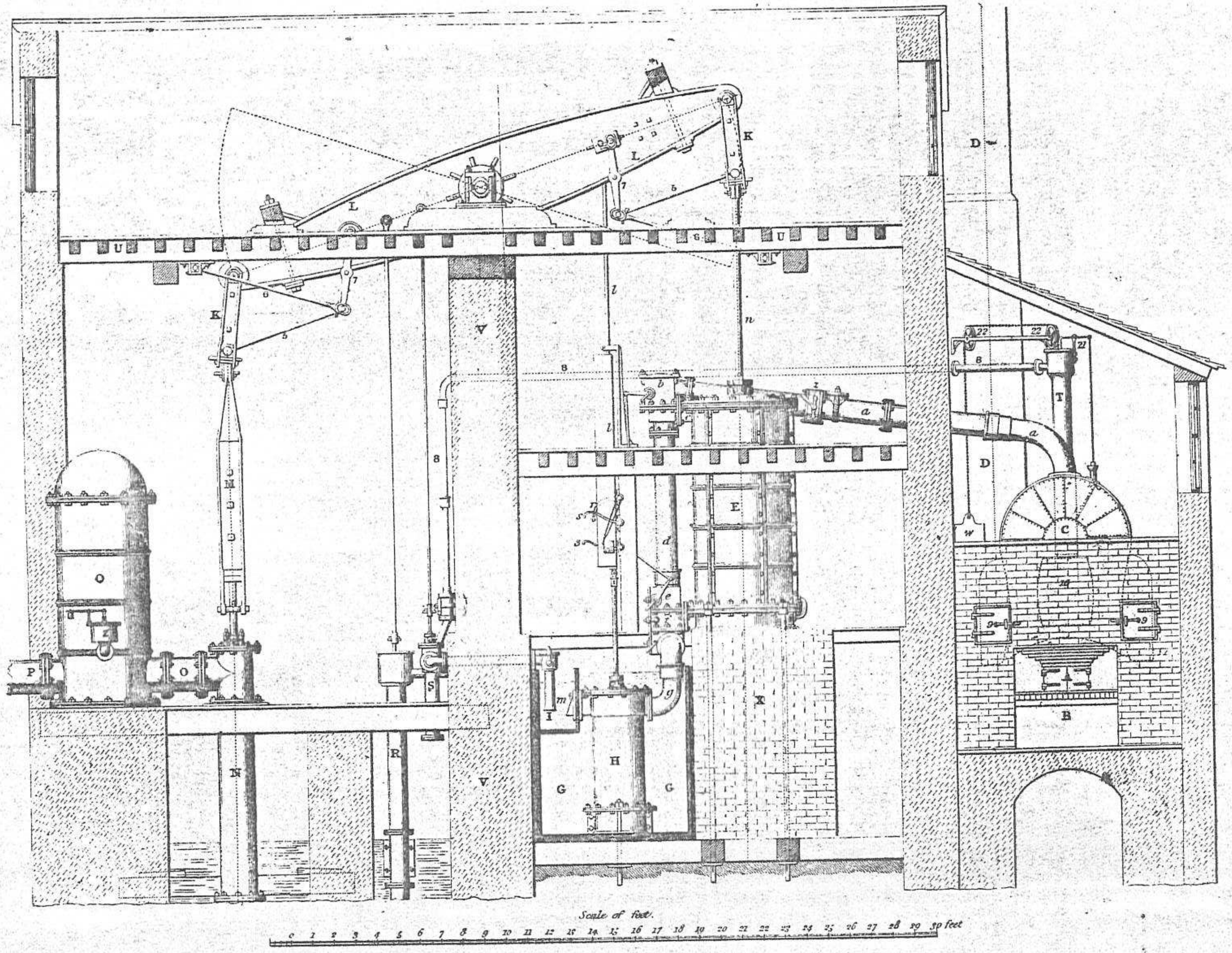


FIG. 18. PUMPING ENGINE WITH ACCUMULATOR, Boulton & Watt, 1803

of the mill the price of wheat had been rising and "great prejudices were excited against the company amongst the lower class of people, to whom it was represented as a monoply highly injurous to the public"[1]. The mill was seen on fire at 6 p.m. on 3rd March 1791; the event was celebrated by street songs and it was thought that the fire was started deliberately[2].

That Albion mills was the wonder of its time we can be in no doubt; the early trials were carried out before crowds of spectators including Sir Joseph Banks[3]; they may have provided the imagery for much of William Blake's work "The living and the dead shall be ground in our rumbling Mills For the bread of the Sons of Albion,..."[4] but all the spectacle grandeur was lost upon the incurable pessimist Watt, who in a letter to Boulton in 1786 said:

"It has given me the utmost pain to hear of the many persons who have been admitted into the Albion Mill merely as an Object of Curiosity. Were there no other loss than the taking up your time it is a very serious one but there are other essential ones which are too obvious to need to be pointed out, among which are that the disgraceful condition in which it has hitherto been has been more likely to do us hurt than good as engineers and the bad management or want of management in oy^{r} [i.e. other] respects must hurt the Credit of the Company - I hear from different quarters enough to convince me that we are looked upon by the serious common sense man as vain and rash adventurers and that our talking of what we can do is construed into either a want of ability to perform it or the foolish cry of Roast beef[3] - My natural hatred of ostentation may perhaps make me feel these things too strongly, but surely those who say so think they have some reason for the observations and it cannot happen that the most pointed of them can come to my ears, considering how little company I keep - Among other things I heard some time ago that on a certain day there was to be a Masquerade at the A M, and this from persons no ways connected with us & who had heard it as com^{n} Birm^{m} talk - and I felt it as a severe reproach Considering that we are much envied at any rate, everything which contributes to render us conspicuous should be avoided, let us be content with doing"[5].

1. Farey: op.cit., p.443.
2. Dickinson & Jenkins: op.cit., p.167. A letter from Rennie to Watt states explicitly that he though the fire was accidental.
3. Dickinson & Jenkins: op.cit., p.165.
4. W.Blake: Jerusalem, 1.49-50, Complete Writings Edited G.Keynes, Oxford 1969 p.673. For arguments in favour of connection between Blake and Albion mills see B.Blackstone: English Blake 1949, and J.Bronowski: "William Blake and the Age of Revolution" 1972. The argument against is given by D.V.Erdman: Blake: Prophet against Empire, 1954. I am inclined to agree with Erdman, 'Albion' was to Blake a symbol of the whole of England and the whole of mankind and that Blake's use of 'Albion' and 'Mill' is simply coincidence, he does not anywhere refer to 'Albion Mill' or 'Albion's mill', Erdman:p.368fn.
5. Boulton Papers: Watt to Boulton, Apl.17 1781. Quoted in Dickinson & Jenkins: op.cit. p.64

To be fair Watt's pessimism and concern was not unfounded, both Boulton and Watt lost money in the venture[1]. But out of their involvement in the venture came many new ideas, including one "... for regulating the pressure or distance of the top mill stone from the Bed stone in such a manner that the faster the engine goes the lower or closer it grinds & when the engine stops the top stone rises up & I think the principal advantage of this invention is in making it easy to set the engine to work because the top stone cannot press upon the lower until the mill is in full motion; this is produced by the centrifugal force of 2 lead weights which rise up horizontal when in motion & fall down when ye motion is decreased, by which means they act on a lever that is divided as 30 to 1, but to explain it requires a drawing"[2].

Before the end of the year a drawing of a governor (reproduced aa figure 19) to be used to control the opening of a throttle valve and hence the speed of a steam engine, is in existence[3]. A further design appeared in September 1790, and by the end of 1790, Rennie was pressing for governors to be sent to him in London, to satisfy the needs of several engine proprietors[4].

Watt was successful in applying the governor to the steam engine; the idea had however occurred to others and Stuart says that "A Mr. Clarke, of Manchester, suggested the application of this fine mechanism to the regulation of the flow of steam from the boiler into the cylinder"[5]. And patents were extant for the use of the flyball governor to regulate the speed of a windmill. Mead's patent covers the use of a governor attached to the drive shaft to adjust the amount of canvas carried by the windmill sail[6]; Hooper's mechanisms use flyweights located on the sails themselves: the weights are free to move along the sails under the influence of the centrifugal force (a balance arrangement counteracts the gravitational force) and the movement adjusts the area of the sail presented to the wind[7]. There is no evidence that either of these methods proved successful in regulating the speed of a

1. Boulton lost £6000 and Watt £3000, see Dickinson & Jenkins: op.cit., p.65.
2. B & W Colln: Boulton to Watt, 1788 May 28 quoted in Dickinson & Jenkins: op.cit., p.220.
3. Drawing dated 13th December 1788, Dickinson & Jenkins: op.cit., p.221.
4. ibid, p.222.
5. Stuart: op.cit., p.360. This could perhaps have been Dugald Clarke who attempted to produce rotary motion from the Newcomen engine - see Stuart p.279. Nicholson in his Journal Vol.II April 1798 p.46 claimed that a Mr. Bruce of the admiralty had invented the governor and 'applied it to a crane' this was no doubt one of the many mechanisms used to regulate the overrun on a crane.
6. Thomas Mead: B.P., 1628, 15th Nov. 1787.
7. Stephen Hooper: B.P. 1706 29th Oct. 1789.

windmill. Neither is there any definite evidence that the governor was used on a waterwheel or steam engine prior to Watt's adoption of the device[1].

Watt did not attempt to patent the governor despite evidence that others were copying it[2]. But he did attempt to gather evidence against the possibility of a challenge to his right to use the governor[3]. J. P. Dearman, apparently in reply to a request from Watt for information on the use of the lift tenter says: "I am told the regulator for millstones has been used about us here 20 or 30 years ago"[4]. There is, however, no evidence of its widespread use prior to the patents of Hooper and Mead, and e.g. Smeaton, who could be expected to be aware of current developments, makes no mention of the lift tenter in his windmill design of 1782[5].

The use of the governor spread rapidly, not only in application to steam engines, but also to waterwheels[6] and to the regulation of prison treadmills[7]. Soon it was installed on practically every steam engine and water wheel, and for over 70 years its design remained virtually unchanged.

1. Dickinson & Jenkins: op.cit., p.220.
2. Dickinson & Jenkins: op.cit., p.221. In 1793 there was a report that an engine builder in Leeds was using the governor.
3. See letters from Dearman's and Warde, ibid, p.222.
4. B & W Colln: J.P.Dearman to Watt, 1793 Dec. 24. Quoted in Dickinson & Jenkins: op.cit., p.222.
5. Smeaton: op.cit., Vol.II, p.396.
6. A.Rees: The Cyclopaedia or Universal Dictionary of Arts, Sciences and Literature, 1819. Article on Mill-Work.
7. A Venetian fly, a form of windmill was attached to the treadmill and "... when the speed exceeds what is above stated, of two revolutions of the Tread-mill per minute, the governor balls fly open, and close the shutters, and by thus increasing the resistance check the velocity; ..." (87) "The above method of regulating the velocity of the wheel, however, although very effectual, has been objected to, as it requires a large and unsightly sort of apparatus; Mr. Cubit has therefore invented another method which is not seen outside the prison walls, as the fly generally is. This consists of three, four, or more large blacksmiths bellows, or bellows of that kind, but without valves, so that the receiving and delivering the air is effected at the same aperture or nozzle. One board of these bellows is connected with a crank worked by the mill, and the adjustment for regulating the speed is as follows. The nozzles or openings of the several bellows are brought into one plane in the face of a frame, and a slide with proper openings is made to pass over these apertures, and thereby to open or close them to any extent. The slide is connected with the governor in such a way, that when the speed ..." P. Barlow: Encyclopaedia Metropolitana, Vol.VIII, 1845, p.123.

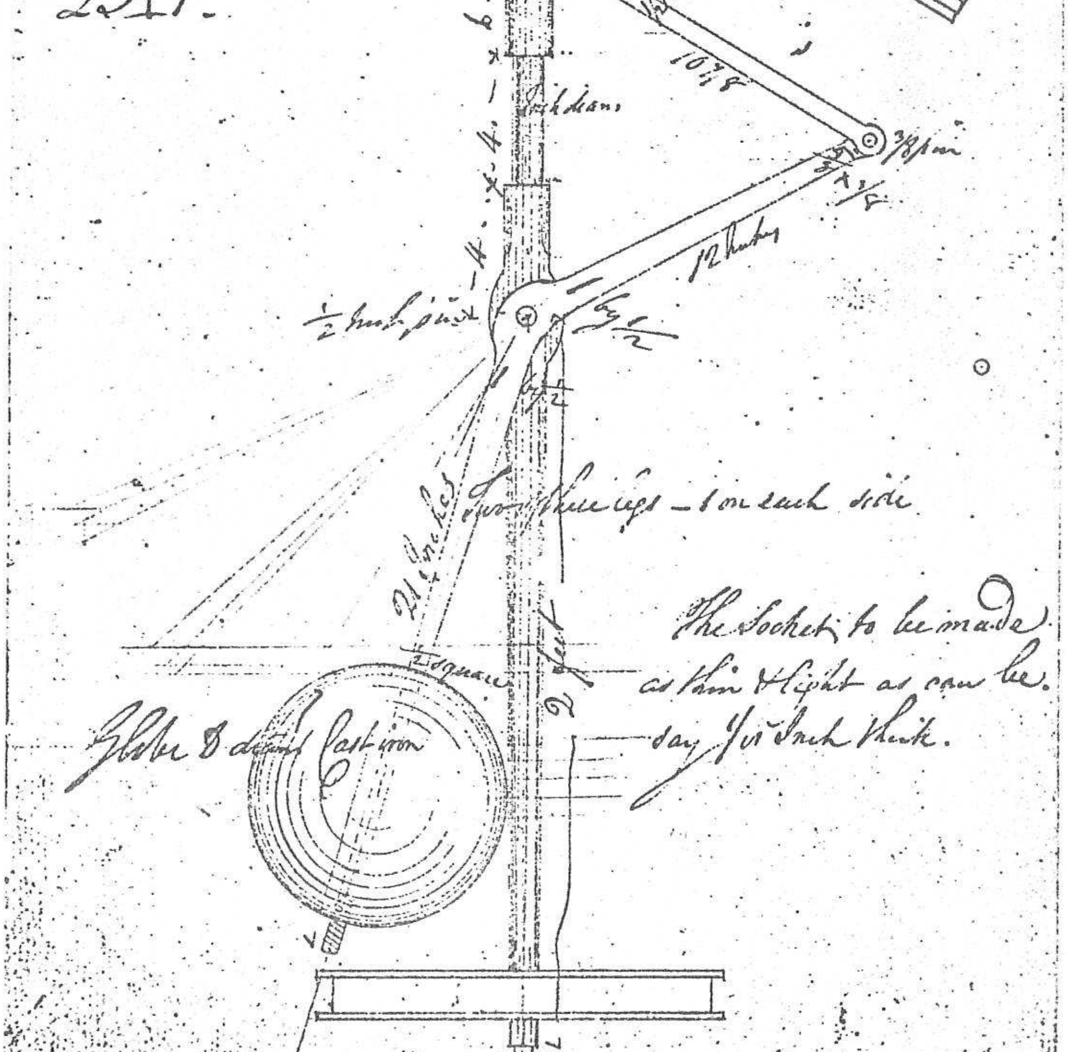


FIG. 19. DRAWING OF GOVERNOR FOR LAP ENGINE, 1788

4. Conclusion

The change from 'ponderous beams' to 'uniform or equable motion' was not the result of a process of gradual improvement, based on a sound understanding of the nature of the problem; rather it was through the use and adaption of existing devices to meet the practical problems as and when they arose. Changes were occurring; equilibrium theories and statics were being replaced by dynamics:

"I consider machines as in motion, performing work. It is evident that this view must lead to or require very different maxims of construction from those which result from the equilibrium of machines, the only point of view in which they have generally been considered"[1].

The importance of energy storage devices, for regulation and smoothing had been recognised. And the practical, controllable prime moves had arrived.

There was no recognition of the difference between open loop and closed loop control, all devices were regulators[2]. It was only after the introduction of the fly-ball governor, the device which has come to epitomise the concept of feedback, that this understanding began to emerge, Gregory in his book A Treatise of Mechanics published in 1806 distinguishes between a flywheel and a 'very different regulator' the flyball governor[3].

For the recognition of the concept of feedback we have to turn to the economic theories of David Hume and more explicitly Adam Smith. Mayr has traced the connections between Watt and Smith (they were both friends of Joseph Black), and has shown that Smith had a good knowledge of contemporary technology, but he is forced, somewhat reluctantly to the conclusion "... that if his Smith's feat of conceptualization was inspired by technology, it would have been impossible without the preparatory work in economic theory by earlier philosophers of laissez-faire"[4]. Certainly an examination of Wealth of Nations, both in draft[5] and final form, shows Smith using technological examples only in an illustrative and not in an analogous manner.

1. Robison to Watt: Oct 22nd 1783. Printed in E.Robinson & D.McKie: Partners in Science: James Watt and Joseph Black, 1970, p.30.
2. Or equalizers. This lack of recognition is perhaps most clearly seen in the equalizing devices proposed in Watt's patent of 1782.
3. O.Gregory: A Treatise of Mechanics, 1806, p.15.
4. O.Mayr: "Adam Smith and the Concept of the Feedback System", Tech. & Cult. Vol.12 1971, pp.1-22.
5. W.R.Scott: Adam Smith as Student and Professor, 1937, contains an early draft of Wealth of Nations, pp.322-356.

The time was not yet ripe for the connection between economics and technology; the breakdown of the rigid, hierarchical economic system had led men to question and to philosophize, but men were not yet ready to indulge in philosophical speculation about everyday mechanical devices. Newton was still subordinate to God - a hundred years were to pass before his brief moment of supremacy - machinery was still expected to follow a rigid, predetermined program; automatons were not yet[1] subordinate to a self-regulating moving force.

1. A.Ure: "The Philosophy of Manufacturers: or an Exposition of the Scientific, Moral and Commerical Economy of the Factory System of Great Britain. 2nd Edn. London 1835 p.18 described the factory system as "... a vast automaton, composed of various mechanical and intellectual organs, acting in uninterrupted concert for the production of a common object, all of them subordinate to a self-regulated moving force".

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6. Appendix

In a notebook belonging to Roger North[1], there are a few pages devoted to mechanical topics. Immediately proceeding two sketches and a description of the Savery engines are sketches and a description of a different kind of steam engine[2]. The main sketch has been redrawn and is shown in figure A1. The description reads as follows:

"The Rising of ye pluggs are ordered to turne a wheel by a toothed barr; [there is a sketch in the margin which shows a toothed rack and pinion] wch, when at the top, is struck loos by a catch, or snack, and then ye barr falls downe, and with its weight turnes ye wheelwork, wch shutts out ye steam from that pipe or socket, by a stop cock, and pari passu opens the other and then that riseth in like manner, and so they play alternately without help. The uses are derived from the wheel wch these rising barrs work upon. thus alternately as ye occasion is, ffor if a Motion be given either to and fro or continual, it may be applyed by wheel work to almost all occasions. But this I saw onely in model"[3].

As can be seen from the sketch the 'pluggs' acted as pistons inside a cylinder and the engine was a high pressure self-acting steam engine. The important feature of this device is that North makes the upstroke of the piston the working stroke used to turn the wheelwork.

Dickinson argues on the basis of the connection between Francis North and Morland that the engine may well have been designed by Morland[4]. He dates the sketches of the Savery engine as 1700-1701 and since the sketch of the other engines preceeds these sketches he concludes that it is of the same date

1. British Museum, North Papers, 'R.North Pictures, Engines and Inventions MS', see H.W.Dickinson: Sir Samuel Morland Diplomat and Inventor 1625-1695 Newcomen Society Extra Publication No.6, Cambridge (1970). Roger North (1653-1734) was a barrister of the Middle Temple. He was Solicitor-General to the Duke of York, and when the Duke became James II he appointed North as Attorney-General to the Queen. North's elder brother Francis, Baron Guildford, held the office of Lord Chancellor and was a friend of Sir Samuel Morland.
2. Dickinson: Sir Sam. Morland, p.78.
3. ibid, p.78 and plates VIII and IX.
4. Dickinson: Sir Sam. Morland, p.80.

or earlier[1]. He argues that it could not be an earlier plan of Savery's since Savery strongly disapproved of the piston engine; nor of Newcomen who was working on the use of vacuum produced by condensing steam. Of the known experiments this leaves Denis Papin's, of whom Dickinson says: "... there is no suggestion that Papin ever contemplated the use of a plunger, nor from what we know of his migrations between Paris and London does it seem possible that North could have seen any model of his before 1701"[2].

Certainly there is no evidence that Papin was in London between 1687 and 1707[3], but need North have seen a physical 'model' or was he using the word 'model' in the sense of a 'drawing' as was still common at the time he was writing?[4] In a letter to Leibniz dated 25th July 1698, Papin says:

"La maniere dont J'emploie à present le feu pour élever l'eau est tousjours sur le Principe de la rarefaction de l'eau. Seulement Je le fais à present d'une maniere bien plus facile à bien executer que celle que J'ay publiée: et deplus, outre la suction dont Je me servoit, J'emploie aussi de la force de la pression que l'eau exerce sur les autres corps en se dilatant, dont les effets ne sont pas borné comme sont ceux de la suction: ainsi Je suis persuadé que cette invention si on la pousse comme il faut, pourra produire des utilitez tres considerables: ... Pour moy, comme Je crois, qu'on peut emploier cette invention à bien d'antres choses qu'à lever de l'eau, J'ay fait un petit modele d'un chariot qui avance par cette force: et il fait, dans mon poele, l'effect que J'en avois attendu: mais Je crois que l'inegalité et les detours des grands chemins rendrons cette invention tres difficile à perfectionner pour les voitures par terre; mais pour les voitures par eau Je me flatteroi d'eu venir à bout assez promptment si J'avois plus de secours que Je n'en ay:..."[5].

1. Dickinson: Sir Sam. Morland, p.78.
2. ibid, p.80.
3. H.W.Robinson: Denis Papin , Notes and Records of the Royal Society, Vol.5, p.47-50.
4. S.O.E.D. Gives first use of word model to mean three dimensional representation rather than 2 dimensional drawing as 1610, and also distinguishes between 'model' and 'working model'.
5. Papin to Leibniz, 25th July 1698, quoted in Gerland: Leibniz und Huygens' Briefmechsel mit Papin, Berlin, 1881, p.233.
"The method in which I now use fire to raise water is still on the principle of the evaporation of water. But now I do it in a way much easier to carry out than that which I published: and furthermore, besides suction which I have made use of, I use also the force of the pressure which water exerts on other bodies when it expands, these effects are not limited as is the case with suction: thus I am convinced that this invention if it is carried on in the proper manner, will be most useful: ... I myself think, that this discovery can be used for many things other than the raising of water, I have made a small model of a cart which is moved by the force: and in my furnace it performs as I expected: but I believe that the uneveness and winding of the roads will make this discovery very difficult to perfect for carriages on the ground: but for carriages on water I hope to master it rather quickly if I have more than is now the case."

The crucial part of this letter are the words "... J'emploie aussi la force de la pression que l'eau exerce sur les autres corps en se dilatant,..." which imply that he was using the generated steam to act on the piston during the working stroke. This corresponds to the description given by North.

Furthermore in 1690 Papin in a letter to Count Philipp Ludwig van Sinzendorff in reference to the use of the atmospheric steam engine says:

"As these tubes would not conveniently put into motion the usual oars, rotary oars would have to be used .... It would be easy to set axles in motion by means of our tube, having the oars fixed at the extremities. It would then only be necessary to furnish the shafts of the pistons with teeth, in order to set in motion small toothed wheels fixed to the axles of the oars. And provided that there were three or four tubes, which would work on one and the same axle, then these could cause a perpetual uninterrupted motion of the axle... The clock maker is obliged every day to fix on to axles, toothed wheels which unfaingly rotate the axle if they move in one direction; but which can freely rotate in the opposite direction without imparting any motion to the axle."[1]

In these two letters we have the essence of the ideas which are present in Roger North's description of a steam engine; this coupled with his use of the word 'model' suggests that the originator of the engine may well have been Denis Papin, and not Morland.

The question which still remains unanswered, however, is did Newcomen know of these ideas which Papin and others were thinking and talking about? There is an obvious connection between Newcomen's buoy which rose up under the action of the pressure of the steam in the boiler, thereby releasing a catch and permitting the engine to make a stroke, and the 'Rising pluggs' which release a catch at the top of their stroke, operate a valve and cause the engine to make the next stroke. But this connection does not necessarily exclude the possibility that Newcomen arrived at the buoy mechanism independently.

1. Papin to Count Philipp Ludwig van Sinzendorff, quoted in F.Klemm: A History of Western Technology, London, 1959, p.222.

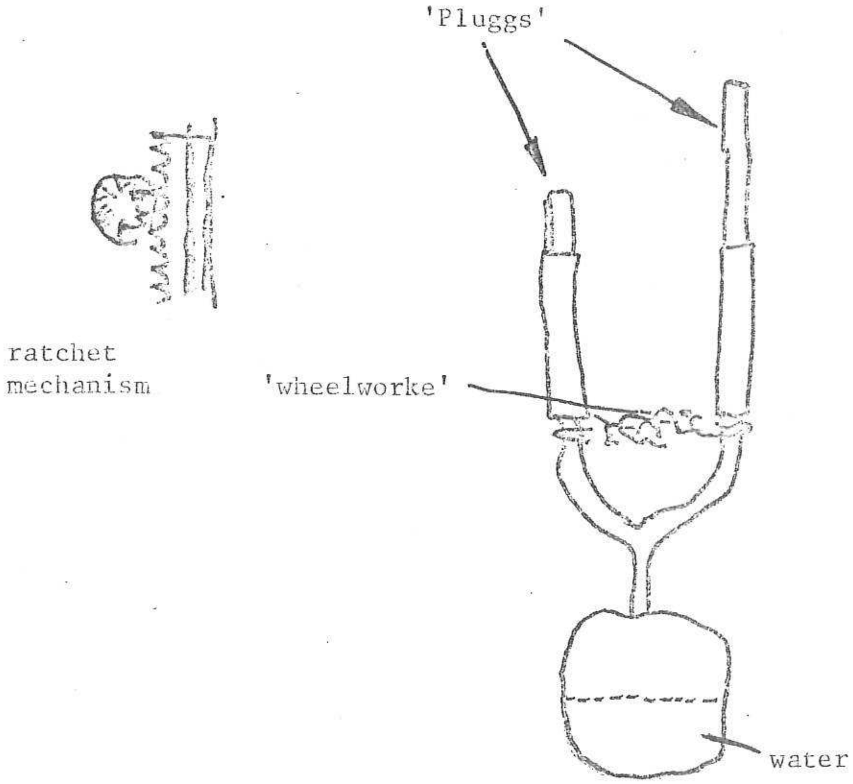

FIG. A1. Sketch of steam engine from Roger North's Notebook.