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TREATISE
ON
MILLS AND MILLWORK

PART I.

ON THE PRINCIPLES OF MECHANISM
AND ON
PRIME MOVERS

COMPRISING THE ACCUMULATION AND ESTIMATION OF WATER POWER;
THE CONSTRUCTION OF WATER WHEELS AND TURBINES; THE PROPERTIES OF STEAM;
THE VARIETIES OF STEAM ENGINES AND BOILERS, AND WINDMILLS

BY

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CHAPTER III.

ON THE CONSTRUCTION OF WATER WHEELS.

In the present age, the same importance is not attached to water power as before the introduction of steam, as has been already shown. Nevertheless, since water is still largely employed in some districts and for certain kinds of work, it is of importance that the machinery for rendering it useful should be constructed upon the best principle, so as to secure a maximum effect. In numerous localities in Europe and America, water is the principal motive agent by which manufacturing processes are carried on; and the time has not yet arrived when it can be dispensed with even in our own country. We shall therefore endeavour to point out the difference between the ordinary and improved forms of water wheels, and to lay down sound principles of construction, accompanied by examples for the guidance of the millwright.

CLASSIFICATION OF WATER MACHINES.

Water may be expended upon water machines, 1st. By gravitation, as in vertical wheels generally; 2nd. By pressure simply, as in the water pressure engine, where the water acts on a reciprocating piston; 3rd. By the impulse of effluent water striking float boards, as in the Poncelet wheel; 4th. By the reaction of effluent water issuing from an orifice, as in the Barker's mill and Whitelaw's turbine; or lastly, by momentum, as in the case of the water ram.

It is not, however, always possible in practice to classify water machines according to the mode in which the water expends its force, and hence it will be more convenient to divide them according to the point at which the water is applied, and the direction in which it passes through the wheel, as in the following summary:—

1st. *Vertical Water Wheels*, the plane of rotation being vertical and the water received and afterwards discharged at the same orifice on the external periphery. These may be subdivided into:—

a. Overshot wheels, where the water is applied over the crest, or near the upper extremity of the vertical diameter.

b. Breast wheels, where the water is applied below the crest at the side of the wheel.

c. Undershot wheels, where the water is applied near the bottom of the wheel, and acts, 1. By gravitation, as in the improvedunders hot wheel; or 2. By impulse, as in the ordinary undershot and Poncelet wheels.

2nd. *Horizontal Wheels*, the plane of rotation being horizontal and the water passing through the wheel from one side to the other. These may be subdivided into:—

a. Horizontal wheels strictly so called, in which the water passes vertically down through the wheel, acting as it passes on curved buckets.

b. Turbines, annular wheels in which the water enters the buckets at the internal periphery, and passing horizontally is discharged at the external periphery.

c. Vortex wheels, in which the water entering at the external periphery flows horizontally and is discharged at the internal periphery.

3rd. *Reciprocating Engines*, in which the water is applied upon a piston and regulated by valves on the same principle as the steam engine.

The Improvements of the Vertical Wheel.—In the present chapter it will be convenient to enter on the consideration of the construction of vertical wheels. Since the time of Smeaton's experiments in 1759, the principle on which vertical water wheels have been constructed has undergone no important change, although considerable improvements have been effected in the details. The substitution of iron for wood has afforded opportunities for extensive changes in their forms, particularly in the shape and arrangement of the buckets, and has given a lighter and more permanent character to the machine than had previously been attained. A curvilinear form for the buckets has been adopted, the sheet iron of which they are composed affording great facility for being moulded into the required shape. It is not the object of the present treatise to enter into the dates of past improvements, but it will suffice to observe that the breast wheel has taken precedence of the overshot wheel, probably from the increased facilities which a wheel of this description affords for the reception of the water under a varying head. It is in most cases more convenient to apply the water of high falls on the breast at an elevation of about 30° from the vertical diameter, as the support of the pentrough is much less expensive and difficult than when it has to be carried over the top of the wheel. In cases of a variable head, when it is desirable to work down the supply of water, it cannot be accomplished without a sacrifice of power on an overshot wheel; but when applied at the breast, the water in all states of the river is received upon the wheel at the highest level of its head at the time, and no waste is incurred. On most rivers this is important, as it gives the manufacturer the privilege of drawing down the reservoir three or four feet before stopping time in the evening, in order to fill again during the night; or to keep the mill at work in dry seasons until the regular supply reaches it from the mills higher up the river. This becomes an essential arrangement where a number of mills are located upon the same stream, and hence the value of small regulating reservoirs behind the mill as a resource for a temporary supply.

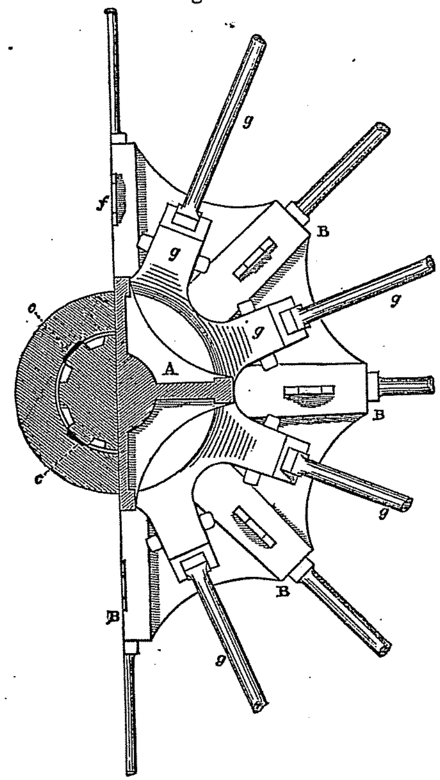
Another advantage of the increased diameter of the breast wheel is the ease with which it overcomes the obstruction of back water. The breast wheel is not only less injured by floods, but the retarding force is overcome with greater ease, and the wheel works in a greater depth of back water.

Component parts of Water Wheels.—Vertical water wheels consist essentially of a main axis resting on masonry foundations, and together with arms and braces forming the means of support for the machine. Chambers for the reception of the water constructed of shrouding, sole-plate, and buckets. A pentrough with sluice for laying on the water, and a tail-race for conveying it away; and an internal or external geared spur wheel and pinion for transmitting the power. These parts we shall treat of successively, before describing the modifications of the vertical wheel.

The main axis is a large and heavy cast-iron shaft carried upon plummer blocks bolted to the masonry foundations of the

wheel-house. It sustains the weight of all the moving parts of the wheel, and in some cases the power is taken from it, when it is subjected to a force of torsion. It is usually cast with deep ribs or wings, calculated to resist the tensile and compressive strain to which they are alternately subjected as the wheel revolves. A section and elevation of the main axis of a water wheel, 20 feet in diameter and 22 feet wide, are shown in figs. 100 and 101.* A A is one half the main axis with its four deep ribs. The part *e* is the journal on which the wheel revolves, and *d* is left square for the convenience of fixing a screw-jack should the wheel require raising. B B B are the recesses for the radical arms of $2\frac{1}{2}$-inch round iron fixed by the keys *f f*; *g g* the corresponding recesses for the braces which pass diagonally across the wheel and alternate with the arms; *c c* are the key beds on the main axis for fixing the main centre. It is difficult to estimate the strain on this shaft when the wheel is on the suspension principle, although the work it has to perform is trifling compared with what it would have to sustain in the event of the power being taken from the axle. In the latter case the wheel has to sustain not only the weight of the wheel and the water in the buckets, but also the force of torsion, as the power is transmitted from the periphery through the arms and axle to the main gearing of the mill.

Fig. 100.



* The wheel is shown in Plate IV. Fig. 110 is also an enlarged detail drawing of this wheel.

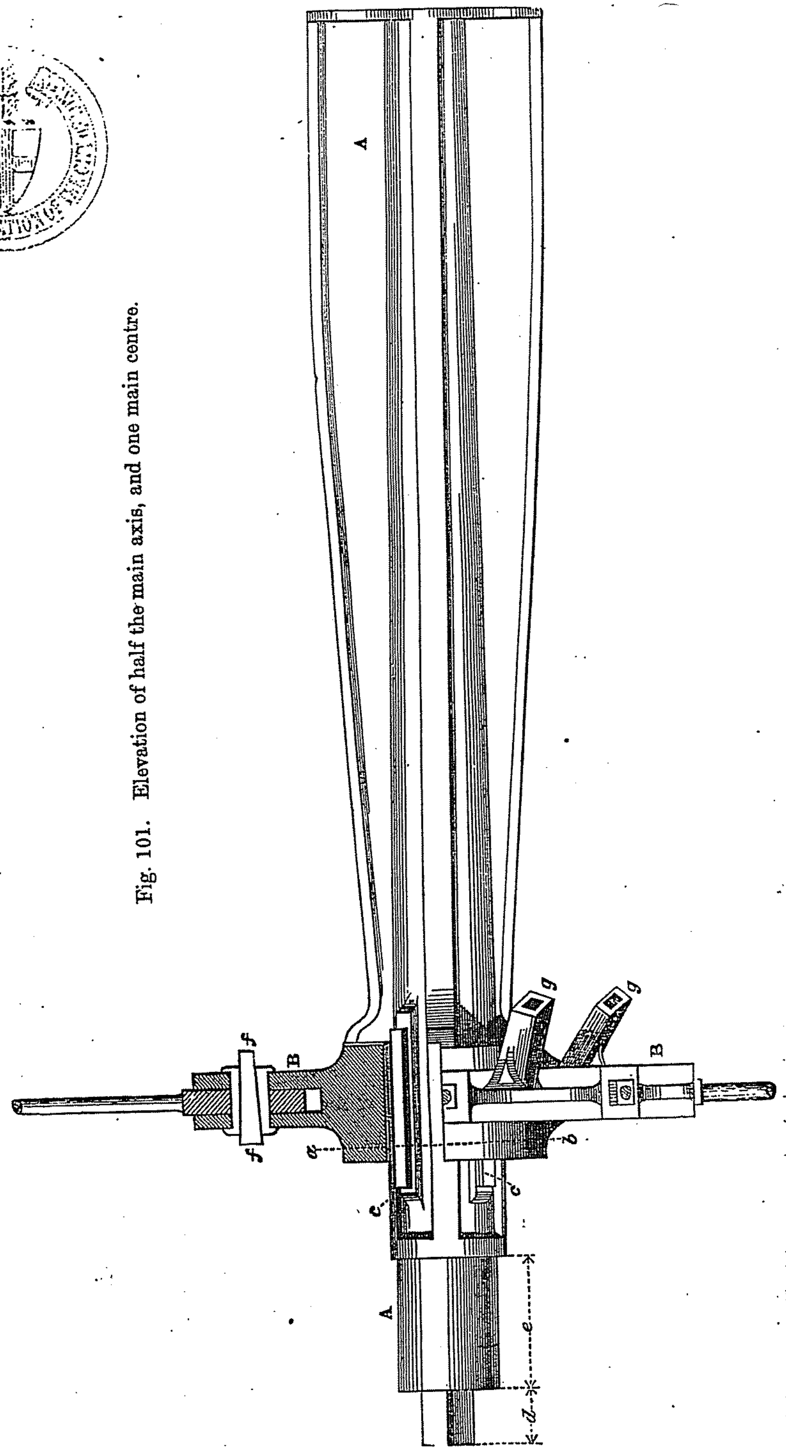


Fig. 101. Elevation of half the main axis, and one main centre.

The following table exhibits the dimensions of the journals, which for high and low breast wheels, where the depth of the buckets is nearly the same, I have found effective, and is a summary of my own practice in this respect for the last forty years :—

TABLE OF DIAMETERS OF THE MAIN AXIS JOURNALS OF WATER WHEELS.

Diameter of Wheels in feet	Diameter of Journal for a Wheel				
	5 ft. broad	10 ft. broad	15 ft. broad	20 ft. broad	
	inches	*inches*	*inches*	*inches*	
15	6	7	$8\frac{1}{2}$	10	The lengths of the bearings are usually equal to one and a half diameters of the journal.
18	$6\frac{1}{2}$	$7\frac{1}{2}$	9	11	
20	7	8	10	12	
25	$7\frac{1}{2}$	$8\frac{1}{2}$	11	$12\frac{1}{2}$	
30	8	9	$11\frac{1}{2}$	13	
40	$8\frac{3}{4}$	10	$12\frac{1}{2}$	$14\frac{1}{2}$	
50	$9\frac{1}{2}$	11	14	16	

Tredgold's rule for the diameter of water-wheel journals is that

$$d = \frac{1}{9}(l\,\mathrm{W})^{\frac{1}{3}} \ldots (1)$$

where d = diameter of gudgeon in inches, l = its length in inches, and W = the maximum load placed on it in lbs.; or, supposing the power to be taken off at the loaded side and the pinion to carry the weight of water, W = half the weight of the wheel.

Example.—A wheel 18 feet in diameter and 20 feet broad weighs 34 tons; required the diameter of the gudgeon of the main axis, taking its length at 10 inches.

$$\text{Here, } d = \frac{1}{9}\left(10 \times \frac{34}{2} \times 2240\right)^{\frac{1}{3}} = 8 \text{ in.}$$

Another rule which has been proposed is—

$$d = \frac{1}{25}\sqrt{\mathrm{W}} \ldots (2).$$

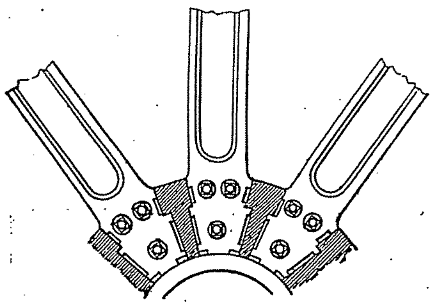
Example.—Taking the same wheel as before—

$$d = \frac{1}{25}\sqrt{\frac{34}{2} \times 2240} = 7{\cdot}8 \text{ in.}$$

where the length is nearly equal to the diameter; but both these give a somewhat smaller journal than in the table above.

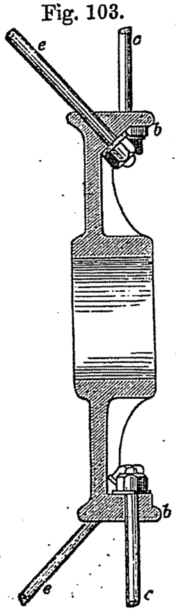
There exists a wide difference of principle amongst mill-wrights as to the mode of attaching the wheel to the axis. It may either be rigidly fixed by cast-iron arms which resist its weight, as a series of columns alternately exposed to a tensile and compressive strain, or it may be supported by tension rods on the principle now most generally practised in the construction of improved iron water-wheels. In the former case the arms are of cast-iron fixed in recesses in a cast-iron main centre, to which they are accurately fitted on chipping strips, and then bolted, as shown in fig. 102. Flat wrought-iron arms are sometimes riveted to the main centre in a somewhat similar manner.

Fig. 102.



It was reserved for Mr. T. C. Hewes, of Manchester, to introduce an entirely new system in the construction of water wheels, in which the wheels, attached to the axis by light wrought-iron rods, are supported simply by suspension. I am informed that a wheel on this principle in Ireland was actually constructed with chains, with which, however, from the pliancy of the links, there was some difficulty. But the principle on which this wheel was constructed was as sound in theory as economical in practice, and is due originally, it is said, to the suggestion of Mr. William Strutt, and was carried out fifty years ago by Mr. Hewes, whilst at the same time Mr. Henry Strutt applied the principle to cart wheels, some of which, thus put together, were for a long time in use. Mr. Hewes employed round bars of malleable iron in place of the chains, and this arrangement has kept its ground to the present time, as the most effective and perfect that has yet been introduced.

Fig. 103.

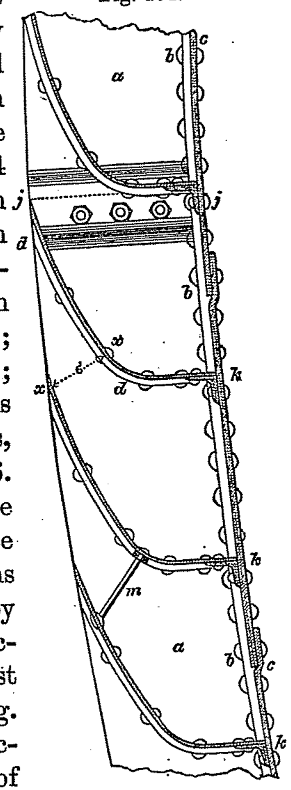


In the earlier construction of suspension wheels the arms and braces were attached to the

centre by screws and nuts, as shown in fig. 103. The arms *c c* passed through the rim *b b*, and the braces *e e*, are set diagonally in the angle of the rim. This arrangement, although convenient for tightening up the arms and braces, was liable to many objections; the nuts were subject to become loose from the vibration in working, so as to endanger the wheel, and to create a difficulty in keeping it truly circular in form. To obviate this, in 1824, I substituted gibs and cotters, on the same principle as those which secure the piston rod of a steam engine, as shown in figs. 100 and 101: the ends of the arms are forged square, and are fixed in sockets in the cast-iron centre, and are there retained by the gibs and cotters *f f* in perfect security from the danger of becoming loose.

The shrouds a a consist of cast-iron plates cast in segments with curved flanches to receive the bucket plates, which are attached to them by bolts or rivets (*d d*, fig. 104), and round the inner periphery a projecting flanch (*b*, figs. 104 and 105) is formed for the reception of the sole plates (*c*). Fig. 104 is a side elevation, and fig. 105 a section of a large shrouding of this description 15 inches deep; *a a* the cast-iron segmental plate of the shroud; *b* the flanch to which the sole plate *c c* is riveted; *d d* the curved flanches and bucket plates; B the bucket. The segments of the shrouds are bolted together by overlap joints, *j j*, shown also in section in fig. 106. The overlap is placed on the bucket side of the shroud to preserve a smooth face on the outside of the wheel. The arms are attached to the shrouds either by riveting, or, according to my own practice, by dovetailing into recesses cast upon the inner face of the shroud. Fig. 107* represents this arrangement in section, and fig. 108 in plan. The ends of

Fig. 104.



* Figs. 104 to 109 are enlarged details of the Catrine Wheels, Plates I. and II.

the arm *c c* are forged into a **T** form, and are fitted into a [illegible]ilar shaped recess on the shroud. To retain the arms in position, it

Fig. 105

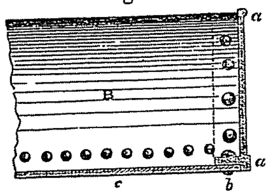
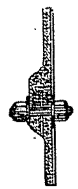


Fig. 106.



is only requisite to give to the recess and **T**-head a dovetail, as shown at *d*. The boss on the shroud must be tapered gradually

Fig. 107.

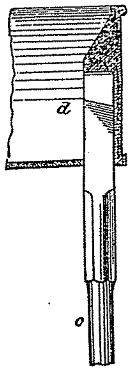
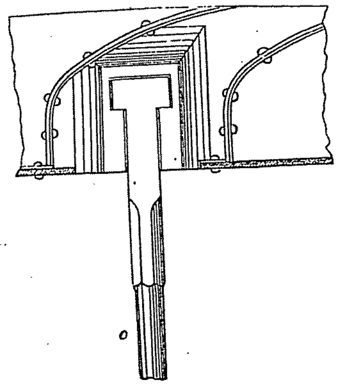
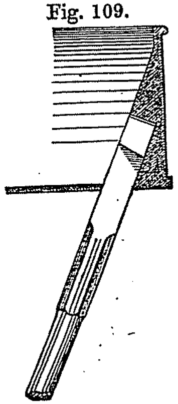


Fig. 108.



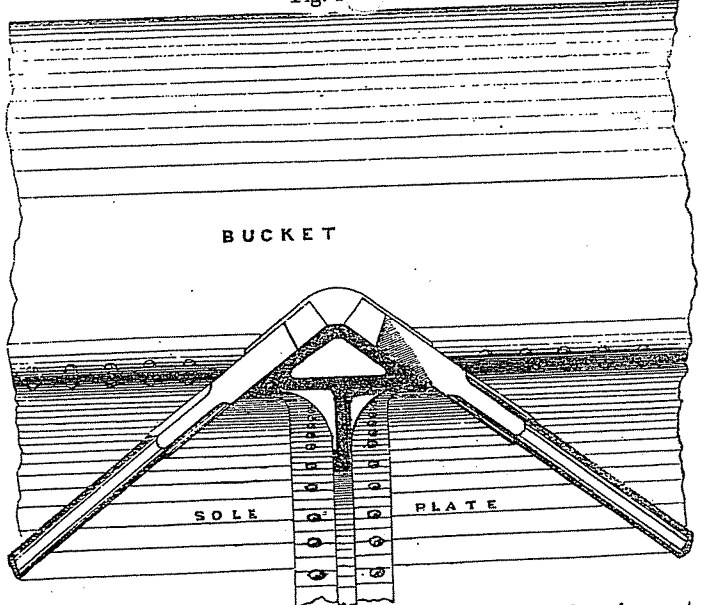
down, to avoid injury in casting from unequal contraction in cooling. The arms are usually 2 to $2\frac{1}{2}$ inches in diameter for almost all wheels, and the braces $1\frac{3}{4}$ to 2 inches.

Fig. 109.



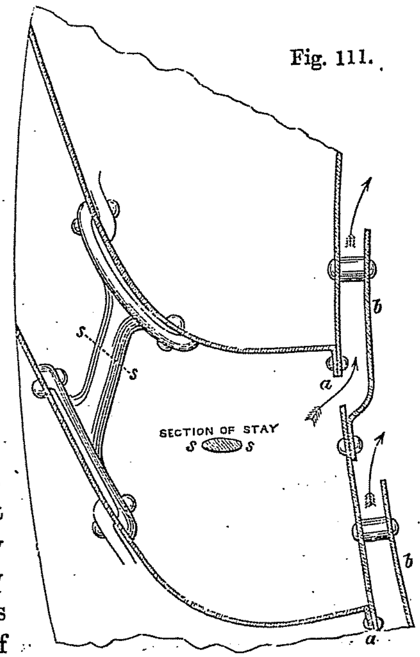
To strengthen the wheel laterally, diagonal arms, called braces, are used (*g g*, *g g*, figs. 100 and 101), and where the wheel is not of great width these braces pass from the main centre on one side to the shroud on the opposite side of the wheel, alternating with the radial arms and fixed in the same manner (fig. 109). Where the wheel is broad I prefer to attach the braces to a middle ring of cast-iron, riveted to the interior of the sole plates in their centre between the shroudings. This ring strengthens the wheel in an important degree, by supporting the bucket and sole plate at their weakest part, where they are liable to

Fig. 1



yield to the weight of the water. The middle ring is cast in segments like the shrouding, and the braces are attached in the way already described. Fig. 110 shows the middle ring of a wheel 20 feet diam. and 22 feet broad.

Fig. 111.



The sole plates are of wrought-iron, $\frac{1}{8}$th inch thick (No. 10 Wire Gauge), riveted together with lap-joints. The buckets are riveted throughout their whole length to the sole plate by a bend at the bottom, or in some cases by a small angle iron (*k k*, fig. 104). For the further support of the bucket plates, at every two feet of their length they are riveted to bucket stays forming a complete ring of auxiliary columns round the wheel at every two feet its breadth. These bucket stays may be of wrought-iron, turned, with two collars, and riveted through each bucket plate, as at *m*, fig. 104, or else of cast-iron, as at *s s*, fig. 111.

The Overshot Water Wheel.—By the overshot water wheel was originally intended that form of wheel in which the stream of water was led *over the summit* of the wheel, and thrown upon it

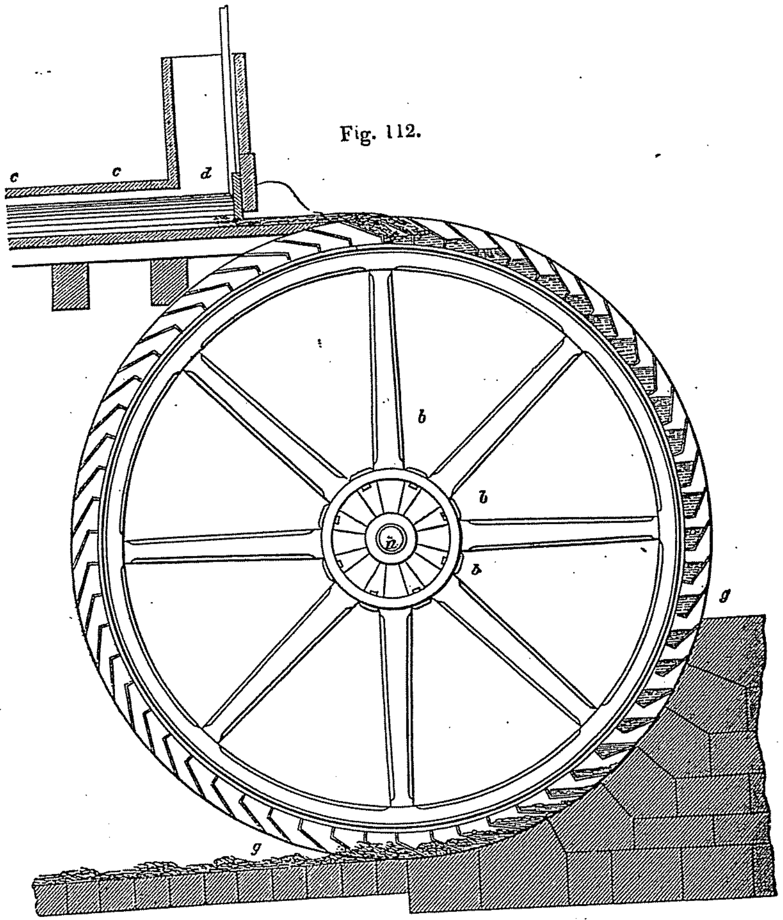


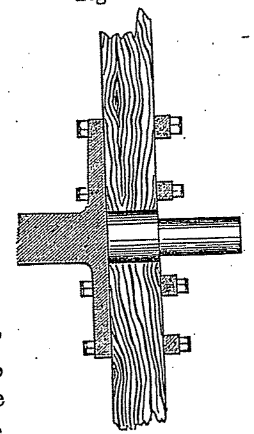
Fig. 112.

just beyond the extremity of the vertical diameter. The water is retained upon the wheel in troughs or buckets, and by its weight continuously depresses the loaded side of the wheel, so as to create a motion of revolution. By a convenient modifi-

cation of the mode of applying the water, however, the stream was laid on to the wheel upon the same side as it approached, by reversing the direction of the spout or sluice, and for this form the name of pitch-back overshot wheel was employed. In present use the term overshot is no longer used strictly, but is arbitrarily applied to all wheels in which the water is laid on near the summit, although high-breast is perhaps a more correct and descriptive designation.

The form of the overshot wheel, as constructed about seventy to eighty years ago, is shown in fig. 112. The wheel revolves on a cast-iron shaft *a*, with broad flanches to which the wooden arms *b b* are bolted, as shown in section fig. 113,* with wedges between them to retain them in place. The water is brought from the dam and carried to the summit of the wheel in a wooden trough *c c*, which is nearly horizontal, as in fig. 112, or has an inclined apron or spout over the wheel, that the water may flow with a velocity somewhat greater than that of the wheel, so as not to be struck by the back of the revolving float-boards, and thrown off the wheel. This apron is usually made to incline at an angle of about 15° with the course, and is 18 or 24 inches long. A sluice or shuttle *d* is generally placed at the end of the pentrough, to regulate the discharge on the wheel.

Fig. 113.



Useful Effect.—Thus provision is made for a constant supply of water falling into the buckets at the summit of the wheel, and by its weight constantly depressing the loaded side, whilst at the bottom it is discharged with the same facility as it was received. Owing to the form of the buckets, however, the water begins to be discharged at a point considerably above the bottom of the wheel, and thus escapes before it has performed all the work due to the fall. The amount of this waste may be reduced—

1. By adopting a curvilinear form of bucket.

* In earlier wheels, in which the main axis is of wood instead of iron, the principal arms are usually placed in parallel pairs extending across the main axis to the shrouding on either side.

2. By only partially filling the buckets.

3. By a close-fitting breast to retain the water on the wheel.

But when decreased as far as possible, this waste is still an important item in the performance of the wheel, and hence the useful effect secured is never equal to the work of the water due to the space through which it falls. The fraction expressing the percentage of useful effect derived from a given quantity of power expended by the water is called the efficiency of the machine, and is found by the formula—

$$m = \frac{100\,\text{U}}{u} = \frac{100\,w\,h}{\text{W H}}$$

$$\text{U} = \frac{m\,\text{W H}}{100}$$

where m is the efficiency of the machine per cent.; u the work of the water employed per minute, or the weight W of the water in pounds multiplied by the fall H in feet, measured from the surface of the water in the pentrough to that in the tail-race; U the useful effect of the machine, or the pressure p in pounds moved by the working point of the machine, multiplied by h, the space in feet through which this point is moved per minute, or the number of pounds raised one foot high by the machine per minute. In ordinary overshot water wheels, the useful effect amounts to about 60 per cent. of the power; or a supply of 12 cubic feet of water per second will give one-horse power for every foot of fall. In the improved iron high-breast wheels, as I have been in the habit of constructing them, the efficiency amounts to 75 per cent., in which case 10·8 cubic feet of water per second will give one-horse power per foot of fall. This is about a maximum effect for water machines, and hence the improved high-breast wheel may be considered as nearly perfect as a water machine.

The waste of water from spilling may to a certain extent be reduced by decreasing the opening of the buckets, but with the disadvantage of at the same time increasing the difficulty of the exit of the water at the bottom of the wheel, and of its entrance at the summit. The waste may be further lessened in an important degree by increasing the breadth of the wheel and the capacity of the buckets, but in general it is not advisable that the buckets should ever be more than two-thirds filled with the average supply of water. The buckets then reach a much lower position before they begin to discharge than when they have been nearly filled. The third means of preventing the spilling of the water is by a curved breast fitting closely to the wheel, as shown in fig. 112, g g, and serving, when accurately fitted, to retain the water on the buckets. With low falls this breast is of considerable importance, and secures a considerable increase of efficiency. But with large wheels for high falls, with small openings in the buckets, it is of no value, and does not compensate for its cost when the buckets are made of the best form, so as to retain the water as long as possible upon the wheel; and in these cases the breast is invariably dispensed with.

The Pitch-back Wheel.—The most important modification of the old overshot wheel is known as the pitch-back wheel, in which the course of the current of water is reversed in the pentrough, and laid on the wheel from the same side at which it approaches. In old wheels it was essential, as the wheel generally worked more or less frequently in back water, that the tail-race should always lie in the same direction as the revolution of the wheel. Hence, when the position of the waste water culvert was fixed by other circumstances, it often happened that the millwright was driven to the use of the pitch-back wheel to meet the conditions of the case, and the advantages of this form of wheel were thus forced on his notice. It was perceived that by increasing the diameter of the wheel the water might be laid on at a distance from the summit, and it was shown theoretically that a larger useful effect would be secured by laying it on at about 25° to 30° from the summit than if it took the water over the top. And in this way, when the introduction of iron gave sufficient facility for the construction of wheels of large diameter, the high-breast wheel was adopted, and has maintained its ground to the present time as one of the most perfect and economical machines.

Direction of Tail-race.—It is no longer necessary that the flow of the tail-water should be in the direction of the wheel's revolution. On the contrary, I frequently take it in the opposite direction or at the side, according as the circumstances of the case determine the position of the wheel and the point of discharge. The old plan of setting

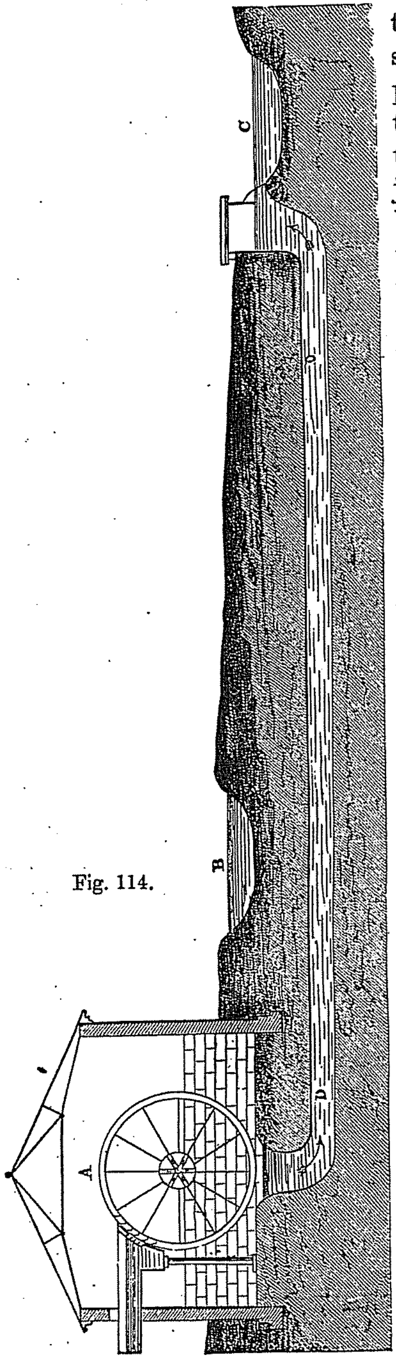
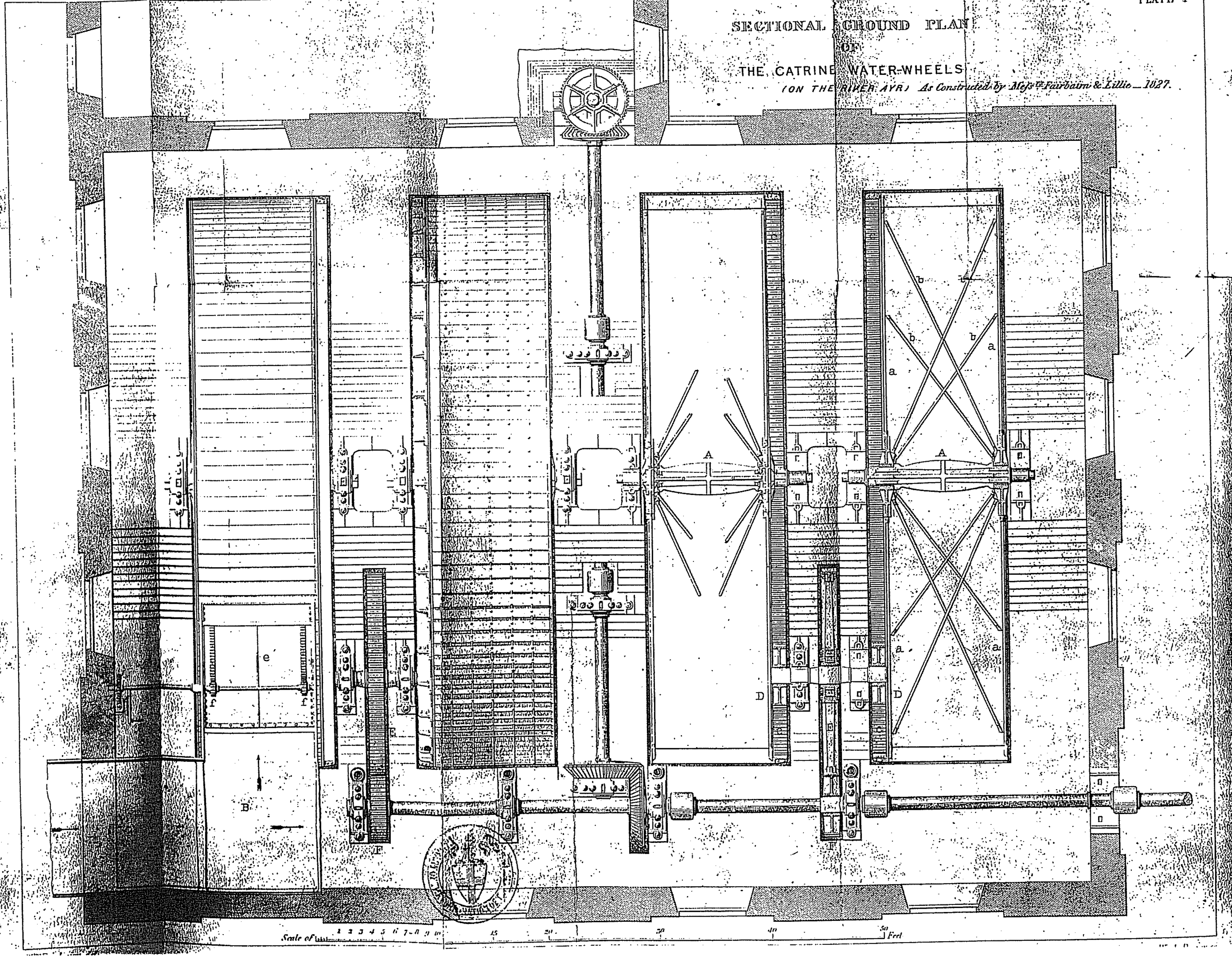


Fig. 114.

the wheel parallel with the stream is no longer requisite provided proper care is taken to give a sufficient outlet to the water. To effect that object it is essential to sink the bottom of the tail-race two or two and a half feet beneath the bottom of the wheel, and that depth should be continued to the river, so as to form the tail-race into a canal with the water flowing gently and with a comparatively slow motion from the wheel. In this arrangement the bottom of the wheel, when standing in an ordinary condition of the river, is 8 or 9 inches above the water in the tail-race, so that its motion cannot be impeded, and there is left ample space for the rise occasioned by the continuous discharge from the buckets during the working of the wheel. To show how immaterial is the direction of the tail-race, I may add that I have in some cases formed the tail-race into an underground tunnel, in the shape of an inverted syphon. Fig. 114 shows this arrangement as adopted for a mill in 1832, to secure an increase of fall: A shows the wheel and wheel-house, in which originally the wheel was 24 feet in diameter, the fall 22 feet, and the tail-

PLATE 1

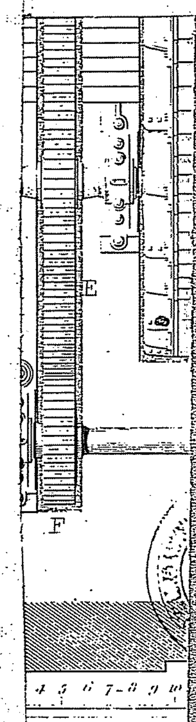


water conveyed direct into the ri
replacing this wheel by a new one,
advantage of a bend in the river, a
to c, an increase of about 6 feet
Hence a wheel 32 feet in diameter
28 feet; and for the tail-race a t
nearly a quarter of a mile long, an
the river at B, so as to meet the str
field at c. The substratum being
shale, afforded every facility for th
when complete, the flow of water t
sensitive, that only a few gallons
the trumpet mouth at A, immed
discharge into the river at c, at
nearly a quarter of a mile. The
ment caused its adoption in othe
were favourable for carrying it ou

The Catrine High-breast Wheel
the construction of the improve
applied at the Catrine Works in
1825 and 1827, on a fall of forty-
sideration the height of the fall,
their power and the solidity of t
the present day among the best a
the kind in existence. They ha
of thirty years, during which tim
no repairs, and they remain nea
were erected.

It was originally intended t
at the Catrine Works; but only
Preparations were made, howeve
the event of an enlargement of
tricts, and more power being
extension has not as yet been
are working to 240 horses' powe
except in very dry seasons, whe
steam-power, to turn the whole

Plate I. is a plan of the whee
the wheels, and the arrangeme



water conveyed direct into the river Eagley, at B. When replacing this wheel by a new one, it was found that by taking advantage of a bend in the river, and conveying the tail-water to C, an increase of about 6 feet of fall could be obtained. Hence a wheel 32 feet in diameter was adopted, with a fall of 28 feet; and for the tail-race a tunnel D D was constructed, nearly a quarter of a mile long, and passing under the bed of the river at B, so as to meet the stream on the other side of the field at C. The substratum being composed of hard rock and shale, afforded every facility for the drifting of the tunnel, and when complete, the flow of water through it was so exceedingly sensitive, that only a few gallons falling from the wheel into the trumpet mouth at A, immediately caused a perceptible discharge into the river at C, at a distance already stated, of nearly a quarter of a mile. The perfect success of this arrangement caused its adoption in other cases, where the conditions were favourable for carrying it out.

The Catrine High-breast Wheels.—Plates I. and II. illustrate the construction of the improved iron high-breast wheel as applied at the Catrine Works in Ayrshire, between the years 1825 and 1827, on a fall of forty-eight feet. Taking into consideration the height of the fall, these wheels, both as regards their power and the solidity of their construction, are even at the present day among the best and most effective structures of the kind in existence. They have now been at work upwards of thirty years, during which time they have required little or no repairs, and they remain nearly as perfect as when they were erected.

It was originally intended to erect four of these wheels at the Catrine Works; but only two have been constructed. Preparations were made, however, for receiving two others in the event of an enlargement of the reservoirs in the hill districts, and more power being required for the mills. This extension has not as yet been wanted, as these two wheels are working to 240 horses' power, and are sufficiently powerful, except in very dry seasons, when they are assisted by auxiliary steam-power, to turn the whole of the mills.

Plate I. is a plan of the wheel-house, showing the position of the wheels, and the arrangement of the main gearing. The first pair of wheels is shown in section, to exhibit the main axle, arms, braces, spur segments, and pinions. The other pair are shown in plan, one exhibiting the buckets, and five rows or bucket-stays, while the pentrough, sluice, and regulating gear are shown on the other. It will be seen that the motion of each pair of wheels is transmitted through a common pinion shaft, and thence by another pinion and spur-wheel, by which the velocity is increased to the first motion shaft of one mill, whilst between the two pairs of wheels there is the first motion shaft of another mill geared into the preceding shaft by a pair of large bevel wheels.

Plate II. is an elevation of the wheel-house, with the masonry for supporting the wheels, tail-race, tunnel, &c. The right half of the wheel is shown in section, and the left half in elevation, and there is a section of the pentrough, sluice, and plates, to guide the water into the buckets.

The following are the references to the different parts of the wheel:—

A, main axis.

a a a, arms. *c*, segments.

b b b, braces. *d*, joints of segments.

B, pentrough.

e, sluice with racks. *f*, pinion connected with governor.

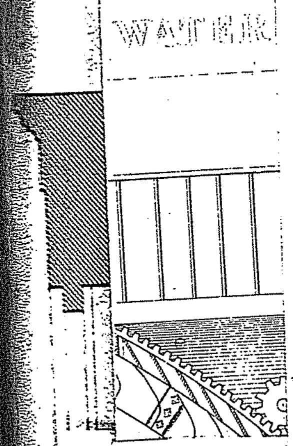
C, tunnel running through the wheel-house, and acting as the tail-race.

D, pinion gearing into internal segmental spur-wheel on shrouds.

E, wheel on the same axis as D, and communicating the power to the pinion F on the first motion shaft.

G, galleries to obtain access to the pentrough and other parts of the wheel.

The water is brought from the reservoirs in a tunnel 10 feet in diameter, through the hill part, and thence in a conduit 12 feet wide, and 5 feet deep, arched over. The reservoirs cover 120 Scotch acres, of an average depth of 8 or 10 feet, giving storeage room for a large supply of water; and the sill of the reservoir sluice, from which the aqueduct bottom is carried



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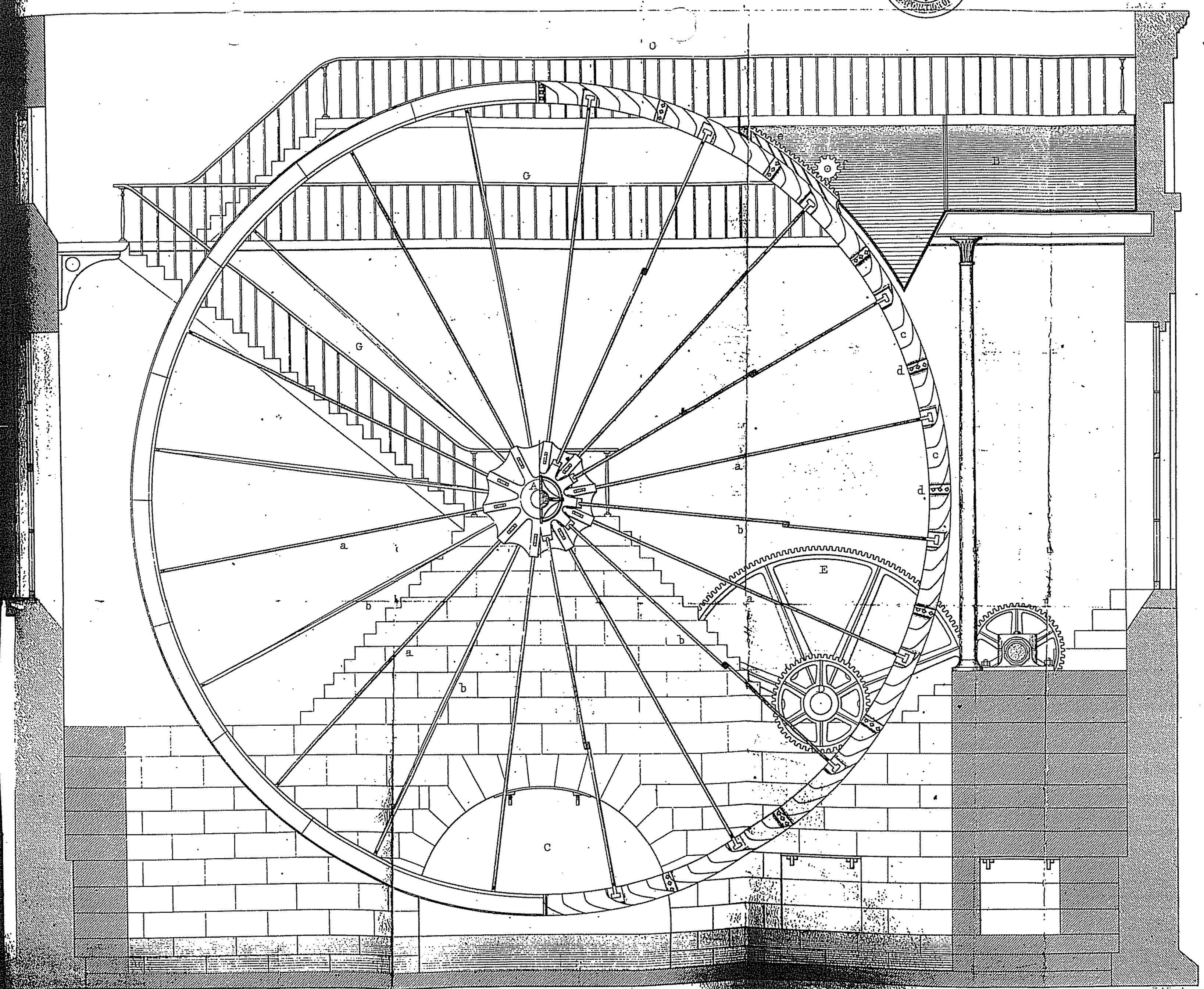


Fairbairn del

level to the pentrough, is 16 inches above the lowest overflow of the sluice on the wheel; hence in dry seasons the water may be drawn off to within 16 inches of the bottom of the lade. At the same time the pentrough is made of a depth of 6 feet, in order that in seasons of plentiful supply the water may be drawn off at the highest level, and the entire fall, as far as possible, rendered effective.

The total supply of water requisite to work the mills when the wheels were started was about 60 tons or 2,150 cubic feet per minute, the wheels revolving at a circumferential velocity of 4 feet a second, or 182 buckets passing each sluice per minute. This gives $\frac{2,150}{182 \times 2} = 5{\cdot}9$ ft. or 6 cubic feet of water nearly for each bucket of the wheels. The whole capacity of each bucket is $17\frac{1}{4}$ cubic feet; hence, when thus working the buckets were just one-third filled.

When working to their full power of 240 horses, however, the fall being 48 feet, this pair of wheels would require,

$$\frac{100 \times 33,000 \times 240}{75 \times 2,240 \times 48} = 98{\cdot}2 \text{ tons of water per minute,}$$

if we suppose the useful effect to be 75 per cent. of the water power expended. Now if we take the circumferential velocity at 5 feet per second, at which the wheel should then run, this would giv ·7 cubic feet of water per bucket, or $\frac{7{\cdot}7}{17{\cdot}25} = \frac{10}{22}$ or one-half nearly, as the ratio of the quantity of water in the buckets to their capacity.

Between these limits these water wheels act effectively and economically.

The wheels are 50 feet in diameter, 10 feet 6 inches wide inside the bucket, and 15 inches deep on the shroud; the buckets are 120 in number, and have an opening of 6 inches; the internal spur segments are 48 feet 6 inches diameter, $3\frac{1}{4}$ inches in pitch, 15 inches broad, and have 560 teeth. The pinions are the same width and pitch, and are 5 feet 6 inches in diameter. The intermediate wheel between the pair of segment pinions is 18 feet $3\frac{3}{4}$ inches in diameter, 16 inches broad, and $3\frac{1}{4}$ inches pitch; and the large bevilwheels are 7 feet in diameter, $3\frac{1}{2}$ inches pitch, and 18 inches broad on the cog, so as to be of sufficient strength to convey, if necessary, the united power of the four water wheels.

When viewed from the entrance, the two wheels already completed have a very imposing effect, from their elevation on stone piers. And as the whole of the cisterns, sluices, winding apparatus, galleries, &c., are considerably elevated, they are conveniently approached in every part. Under the wheels there is a capacious tunnel, terminating at a considerable distance down the river and conveying away the tail-water from the wheels.

TABLE OF SPEED.

Water wheel 50 ft. 0 in. = 1·5 revolutions = 4 ft. per second.

	Diameter.		Revs.		Diameter.		Revs.
Segments,	48 ft. 6 in.	and	1·5	into wheel	5 ft. 6 in.	=	13·3 of shaft.
Wheels A,	18 ft. $3\frac{3}{4}$ in.	and	13·3	into pinion	5 ft. 6 in.	=	44 of main shaft to mill.
Wheels B,	7 ft. 0 in.	and	44	into wheel	7 ft. 0 in.	=	44 of shaft to new mill.
Wheels S,	5 ft. 9 in.	and	44	into wheel	4 ft. 0 in.	=	63 of upright in new mill.

The journals of the main axes of the water wheels and of the pinion shafts are 14 inches in diameter. The first motion shafts are $13\frac{1}{2}$ inches in diameter, and of an average length between the couplings of 19 feet.

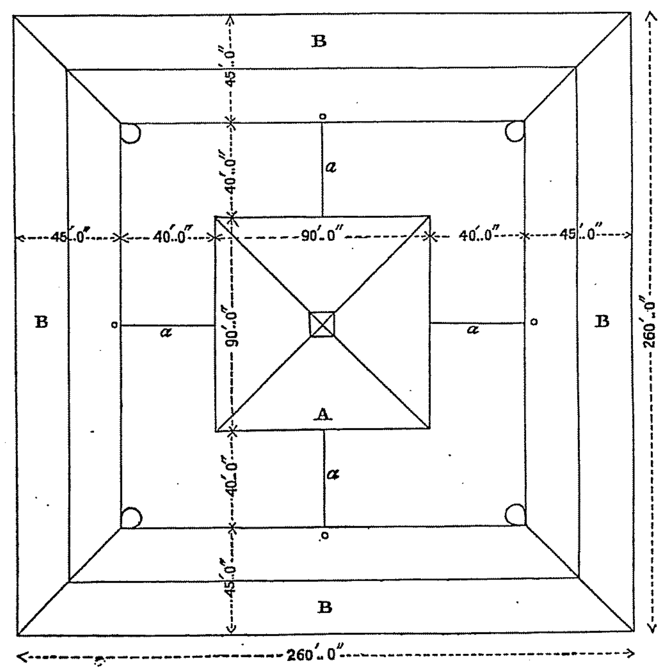
The maximum fall may be estimated at 48 feet 9 inches. The distance from the bottom of the wheel to the floor of the tail-race is 3 feet 6 inches, the average depth of tail-water 2 feet, and the distance from the floor of the tail-race to the level of the water in the reservoirs is 50 feet 9 inches.

I have been more particular in describing these wheels, as they are the first erected upon the principle of concentration and combined action. In former cases it had been the custom to erect the wheels near where the work was required, so that it was not unusual to have three or four wheels at a short distance from each other, working independently. This was the case at the Catrine Works before the large wheels were erected. It was found desirable, however, in extending the works, to have the whole power concentrated in one wheel-house, with a uniform fall, so as to simplify the transmission of the power to the different parts of the mills. This was effected in the manner already described with great success, and the result

has been a continuous and efficient supply of power from 1827 to the present time.

Immediately following the erection of the Catrine wheels, those of Deanston, belonging to the same proprietary, were commenced. The Deanston Works were designed upon a much larger scale than even those at Catrine, as it was intended to erect eight powerful water wheels instead of four, as in the

Fig. 115.



works in Ayrshire. The Deanston Works were erected with two water wheels in the bottom room of the factory about the year 1780, and came into the hands of their present proprietors about 1798 or 1800. After the completion of the alterations in Ayrshire, a similar concentration of the power was desired for Perthshire, and I was requested to prepare both for a renewal of the old wheels and the erection of new ones on a larger and more comprehensive scale. In obedience to these instructions, an entirely new site was selected for the water power, close to the old mills on the River Teith, and provision made for an increased fall, and an improved application of the water power.

The new wheels as then designed were eight in number, and were placed together in a rectangular building adjoining the old mill, but arranged to afford power to an entirely new establishment surrounding the wheel-house, according to the annexed plan (fig. 115), in which the centre building A is the wheel-house, and the buildings B B B B, surrounding it on all four sides, and three stories in height, contained the machinery driven by the wheels. From this design it will be seen how the power, amounting to 800 horses, was given out on each side by the shafting *a a a a*, radiating from the centre of the wheel-house, at right angles to the mills on every side. Another shaft was extended in an underground tunnel to the old mill, where it still gives motion to the machinery in that portion of the works.

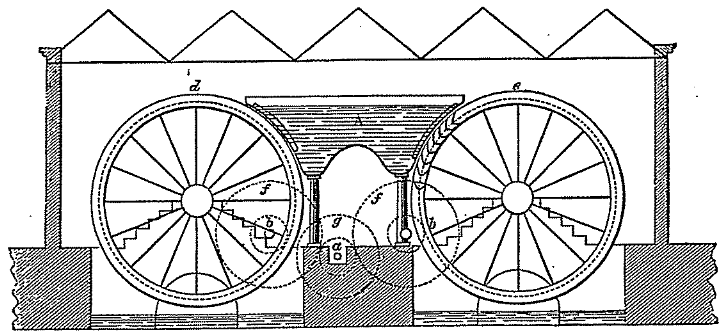
It is much to be regretted that this design was never carried out in its integrity; but the late Mr. James Smith, so well known as the inventor of the subsoil plough and many other ingenious contrivances, altered the plans after having raised one side of the new mill to a height of one story, when unfortunately it was abandoned for a much less convenient and less perfect structure.

As respects the water wheels, the first two were erected by myself—then in partnership with my much respected friend, Mr. James Lillie—and the last two by Mr. Smith, who, with the Cotton Mills, has since carried on considerable engineering works. The remainder have never been erected. There were, however, several novelties in the arrangement of these wheels which it may be desirable to describe at greater length. The River Teith is the principal feeder, and falls into the Forth about a mile above Stirling. The supply in ordinary seasons is about 260 cubic feet per second, and for many months in the year more than double that quantity. The original fall was about 18 feet; but by the erection of a weir higher up the stream, and the construction of a canal three-quarters of a mile long, it was increased to 33 feet, so as to afford, except in very dry seasons, nearly 800 available horses' power. Of late years this has been increased by a copious supply from Loch Vennaquar, the surface of which has been raised at the cost of the Corporation of Glasgow, as a

compensation for the water taken from Loch Katrine, which falls into the Teith for consumption in the city. From Loch Vennaquar, therefore, there is a continuous supply at all seasons.

The augmentation of the fall from 18 to 33 feet nearly doubled the power for the mills, and also the supply of water which was conveyed direct from the weir to the new wheels in the rectangular building. The water flowed into a wrought-iron pentrough A, fig. 116, supported on iron columns, and delivered the water into the wheels on each side. The wheels were 36 feet in diameter, and of the same construction as

Fig. 116.



those at Catrine. Those on one side of the pentrough, *d d d d*, gave off their power by an internal spur gearing, and those on the other, *e e e e*, by an external spur gearing on the shrouds of the water wheels; the shafts carrying the pinions, *b b*, gearing into the water wheel segments, carried also a spur-wheel, *f f*, 18 feet diameter, gearing into a common pinion *g*. This last pinion was on the central shaft, *a a*, passing along the centre of the wheel-house, and giving off motion to the shafts *á á* by the bevel wheels *k*, at the centre of the wheel-house (fig. 117).

Water wheel, 4·1526 ft. circumferential velocity = 2·203 revolutions.

	Ft.	in.		Rev.		Ft.	in.			Rev.	
Segments,	33	8½	and	2·203	into	5	6	pinion	=	13·59	cross shaft.
Wheels *b b*,	18	2½	and	13·59	into	5	6	pinion	=	45·3	of main shaft to mill.
Wheels,	6	0	and	45·3	into	4	2½	wheel	=	65	of upright in mill.

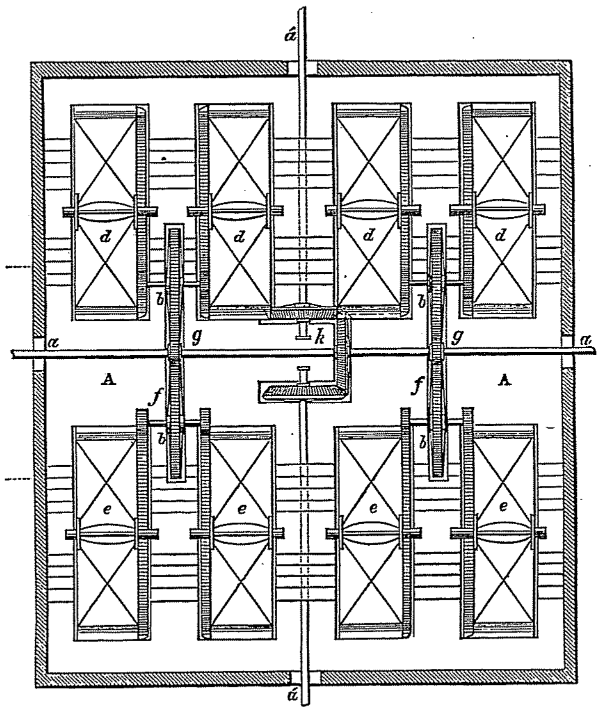
It will be observed that these high-breast wheels have the peculiar advantage of permitting the use of a sliding or holding sluice, for the admission of the water, which can be adjusted to a very variable fall. So that, at whatever height the water may stand, the velocity at which it enters the wheel will be the same, because it falls over the top of the adjusted sluice. But with this advantage they are apt to become liable to the defect of admitting the water with too much difficulty, a defect which was remedied by the principle of ventilation, which I first introduced in the year 1828, under the following circumstances:—

Ventilation of Water Wheels.—Shortly after the construction of the water wheels for the Catrine and Deanston Works, a breast wheel was erected for Mr. Andrew Brown of Linwood, near Paisley. In this it was observed, that when the wheel was loaded in flood waters, each of the buckets acted as a water blast, and forced the water and spray to a height of 6 or 8 feet above the orifice at which it entered. This was complained of as a great defect, and in order to remedy it openings were cut in the sole-plates, and small interior buckets attached, inside the sole, as shown at *b*, fig. 111. The air in the bucket made its escape through the openings *a*, *a*, and passed upwards as shown by the arrow, permitting the free reception of the water from the pentrough. The buckets were thus effectually cleared of air as they were filling, and during obstruction from back-water in the tail-race the same facilities were offered for its re-admission, and the free discharge of the water from the rising buckets. The effect produced by this alteration would scarcely be credited, as, in consequence of the freedom with which the wheel received and parted with its water, an increase of power of nearly one-third was obtained, and the wheel, which remains as then altered, continues, in all states of the river, to perform its duties satisfactorily.

This difficulty in the admission of the water had often been noticed by the early millwrights, and where it interfered with the working of the wheel, their remedy was to bore holes for the escape of the air in the sole-plate or the start of each bucket. Thus, in his 'Mechanical Philosophy,' Dr. Robison gives a similar instance to that of Mr. Brown; a wheel 14 feet in diameter and 12 feet wide was working in three feet of back-water and labouring prodigiously; three holes, each one inch

diameter, were made in each bucket, when the wheel ceased to labour, and its power was increased one-fourth. The objection to holes in the sole-plate or buckets is a certain spilling of the water over the interior of the wheel, which cannot be avoided. But it must be remembered that air being 800 times rarer than water will escape through a hole at least thirty times faster with

Fig. 117.



the same pressure. Hence, the area for the escape of the air may be made very much smaller than the opening of the bucket.

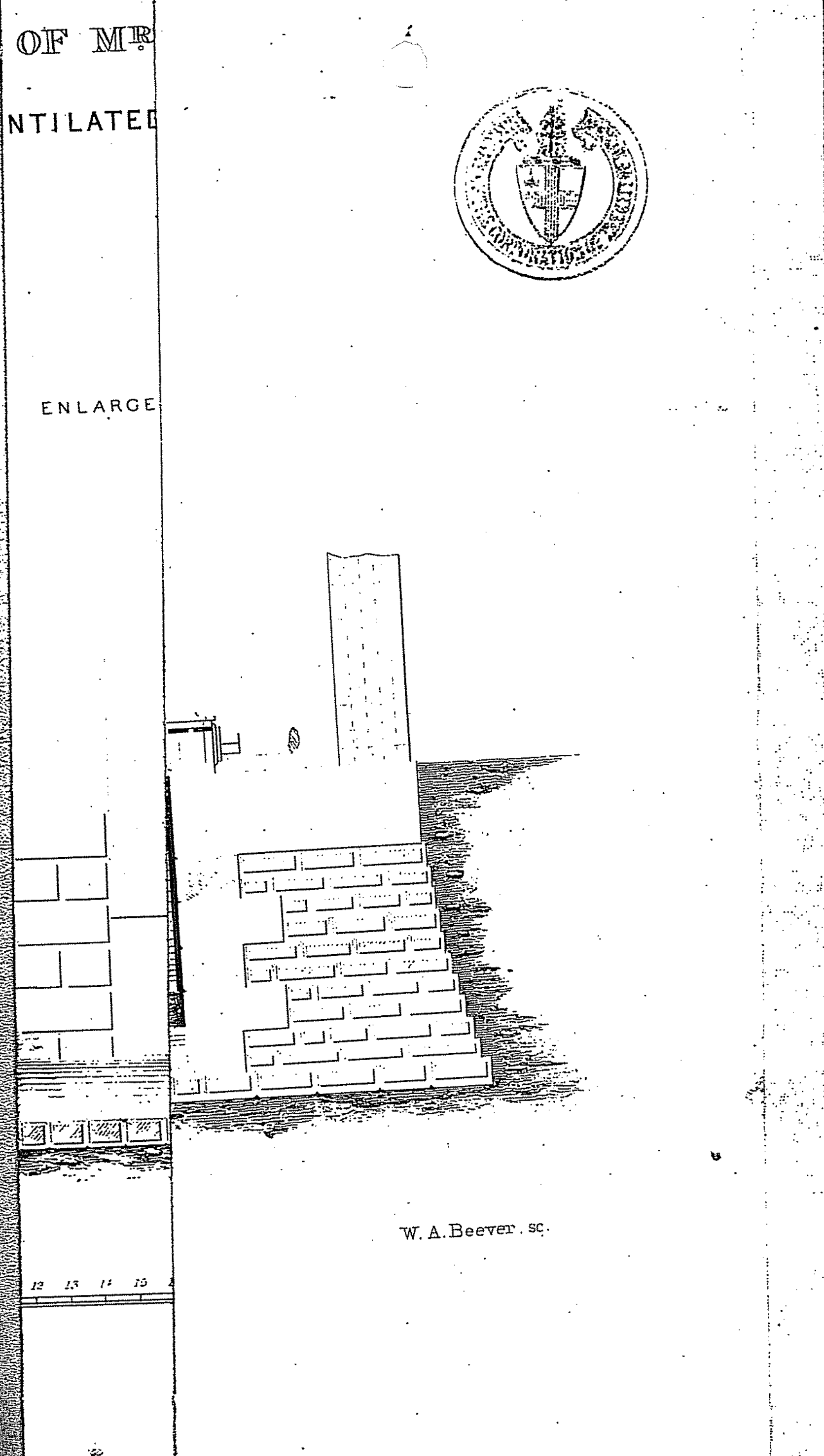
The amount of power gained, and the beneficial effects produced upon Mr. Brown's wheel, induced the adoption of the ventilating principle as a permanent modification of construction. The first wheel thus designed was erected at Wilmslow in Cheshire, and was started in 1828. It was identically the same with that shown in Plate III., and it was closely followed by a further improvement, as shown in Plate IV.

Close-bucketed wheels labour under great disadvantages when receiving the water through the same orifice at which the air escapes. When, as is frequently the case, the water is discharged upon the wheel in a sheet of greater depth than the opening between two buckets, the air is thus suddenly condensed in the bucket, and re-acting by its elastic force throws back the water upon the orifice of the cistern, and thus allows the buckets to pass imperfectly filled. A similar obstruction occurred whenever the wheel worked in backwater, the water being lifted in the rising buckets, the mouths of which being under water the entrance of air was effectually prevented; and the deeper the backwater the more completely they filled with water and the greater became the difficulty in discharging. Many millwrights to remedy this were in the habit of boring holes in the sole near the start of the bucket, and of narrowing the spout or sluice so as to leave room on each side of the buckets for the escape of the air, means which to some extent remedied the evil of the spilling and sputtering of the water, but in most cases occasioned considerable waste of power, from the water being driven through the openings and falling over the interior of the wheel.

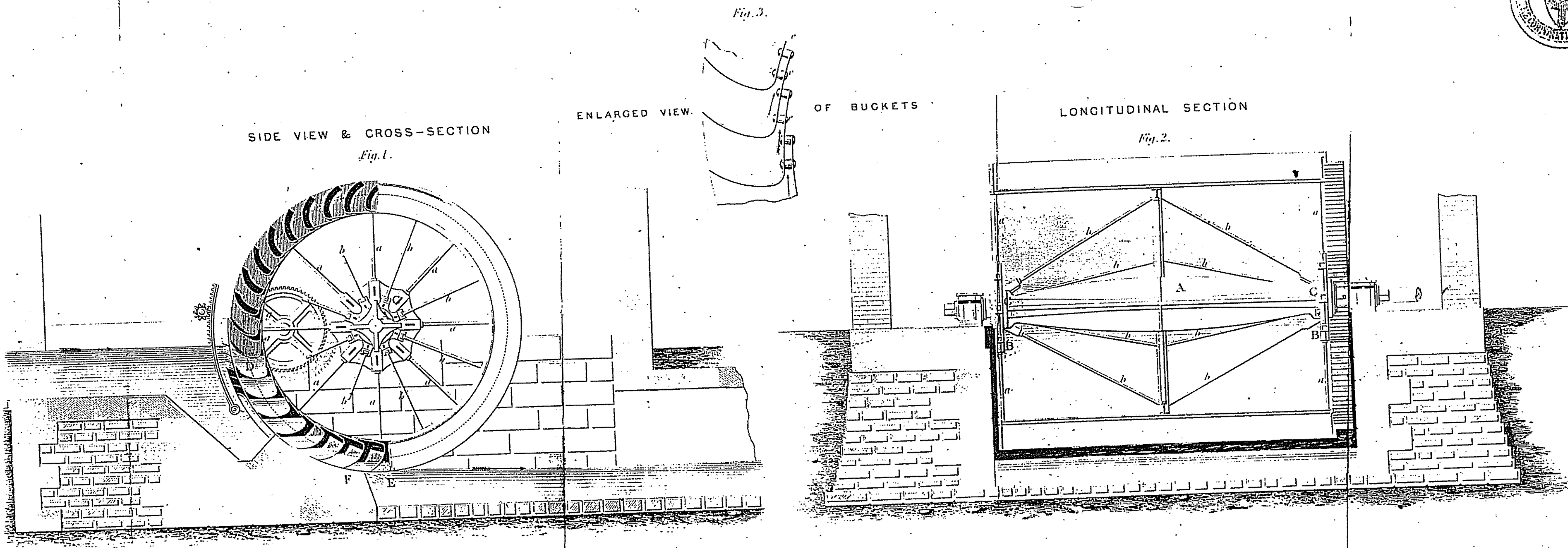
Other remedies have been attempted, such as circular tubes and boxes attached to the sole-plates; but these plans have been generally unsuccessful, owing to the complexity of their structure and the inadequate manner in which they attained the object contemplated. In fact, in wheels of this description it has been found more satisfactory to submit to acknowledged defects, than to incur the trouble and expense of partial and imperfect remedies. In the ventilated wheels about to be described, the perfect escape of the air is effected by very simple means, and great success has attended their application in situations where interruptions frequently arise from excess of backwater or a deficiency of supply.

Low-breast ventilated Wheel.—Plate III. represents a front and side view of a water wheel with ventilated buckets. Portions of the shrouding and segments are removed in order to show a section of the buckets, and the position in which they receive the water.

A is the axle or ribbed shaft, supporting the two main axes, C C, from which the wheel is suspended; B B are the projecting



WITH VENTILATED BUCKETS, WITHOUT SOLE-PLATE.



W. A. Beever. sc.

SCALE OF 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 FEET

London: Longman & Co.

sockets into which the ends of the malleable arms *a a* and the diagonal braces *b b* are keyed. The arms are 2 inches, and the braces $1\frac{3}{4}$ inches in diameter. D represents the buckets, with the shuttle which regulates the admission of the water, and which is made to slide downwards. F the termination of the stone breast, and E the tail-race. This wheel, it will be seen, is arranged as a low-breast.

The principle of the construction of the buckets is more clearly shown on an enlarged scale in fig. 3, Plate III., the sole-plate being abandoned and the bucket plates bent round and prolonged upwards so as to overlap one another, leaving an opening, indicated by the arrows, for the escape of the inclosed air. The bucket plates are connected together by tubular ferules, or stays, through which a rivet is passed, and riveted on each side.

The wheel should always, as in this plate, be placed above the tail-water, and not, as in the older forms of wheels (fig. 112), be carried down to the level of the tail-race floor; and the breast of wood, iron, or stone, but usually the latter, which is of so much importance for low falls in retaining the water on the wheel, should break off about ten inches from the extremity of a vertical diameter of the wheel. In fact, the benefits of this form of breast and tail-race are so great, they should be strictly carried out where it is desirable to make effective use of the fall.

In high-breast wheels of 25 feet in diameter, and upwards, the breast is not required, as the buckets having narrower openings, and their lips extended nearer to the back of the following buckets, retain the water longer on the wheel. In this case the loss from spilling constitutes too small a percentage of the power to compensate for the expense of a lofty and close-fitting breast. In some cases the breasts have been composed of iron and wood, but in the best constructed they are of masonry, and allow little or no space between them and the wheels. It is, however, necessary to be cautious that extraneous matters do not in that case gain admission to the buckets, as by jamming between the buckets and the curb they might cause disaster.

The preceding statements, so far as relates to the method of ventilation, have been principally confined to the form of bucket and description of water wheel suitable for low falls. It will now be necessary to describe the best form of breast wheels for high falls, or falls of from one-half to three-fourths of the diameter of the wheel.

High-breast ventilated Wheel.—A water wheel of this kind, constructed for T. Ainsworth, Esq., of Cleator, near Whitehaven, is represented in Plate IV. It is 20 feet in diameter, 22 feet wide inside the bucket, and 22 inches deep on the shroud. It has a close riveted sole, composed of No. 10 wire gauge iron plate, and the buckets are ventilated from one to the other, as shown on a larger scale in fig. 3. The fall is 17 feet, and the water is discharged upon the wheel by a circular shuttle, A, which is raised and lowered by a governor as circumstances require. By this arrangement the whole height of fall is rendered available, and the water in dry seasons may be drawn off three or four feet, in order to afford time for the dam to fill in the periods during which the mill is stopped.

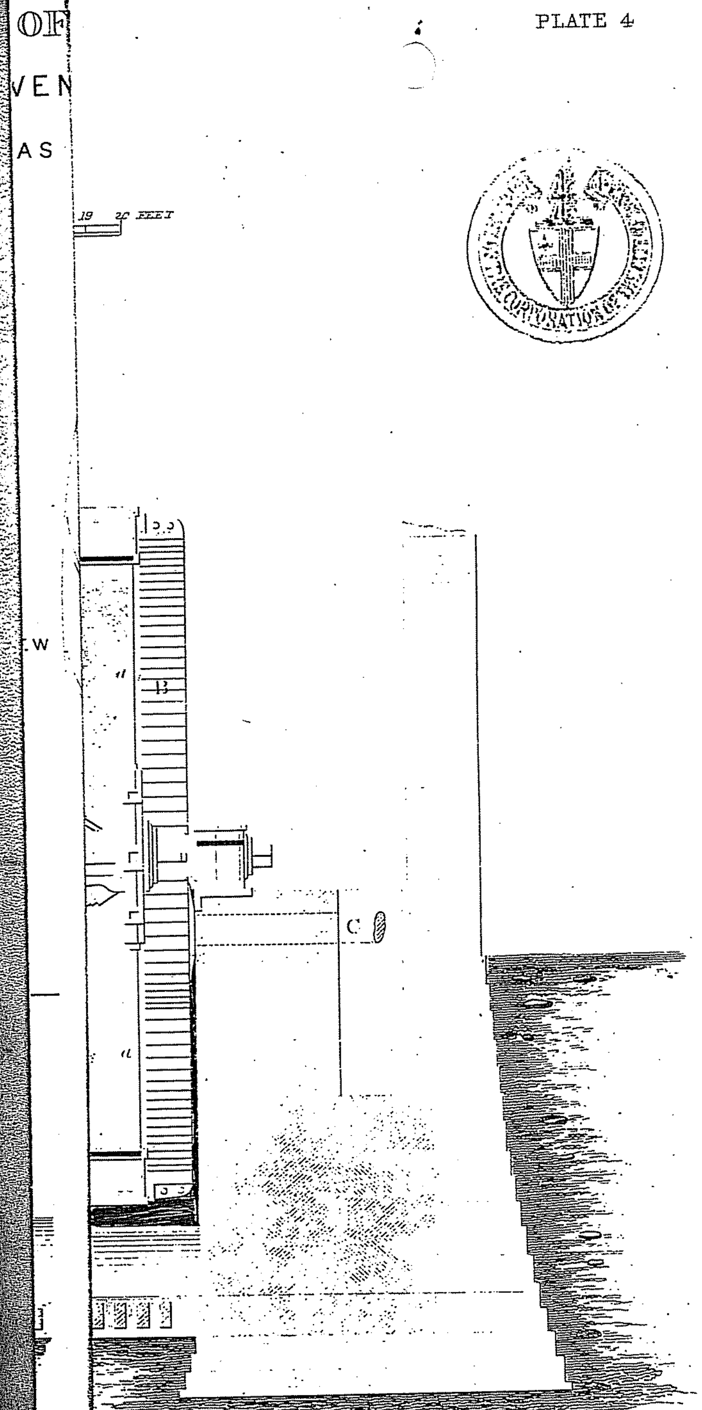
The power is taken from each side by two pinions working into the internal spur segments B B, and these again give motion to shafts and wheels at C C, which communicate with the machinery of two different mills, at some distance from each other.

Arrangement of Gearing.—The position of the pinion, or the point where it gears into the spur segments on the water wheel, whether internal or external, is of importance in every water wheel, but pre-eminently so in those constructed on the suspension principle, which are indifferently prepared to resist the torsive strain to which they would be subjected if the power were taken from the unloaded arc of the wheel. Water wheels of this construction, with malleable iron rods only two inches in diameter for their support, could not resist the strain, but would twist round upon the axle, and destroy the wheel.

It is necessary, therefore, in every case, to take the power from the loaded side of the wheel, as near the circumference as possible, in order to throw the weight of the water directly upon the pinion without transmitting it through a larger arc of the wheel than is absolutely necessary. For this purpose the spur pinion should be below the centre of gravity of the water on the wheel, and therefore more or less below the extremity of the horizontal diameter.

In the old water wheels, where the power was generally taken

PLATE 4



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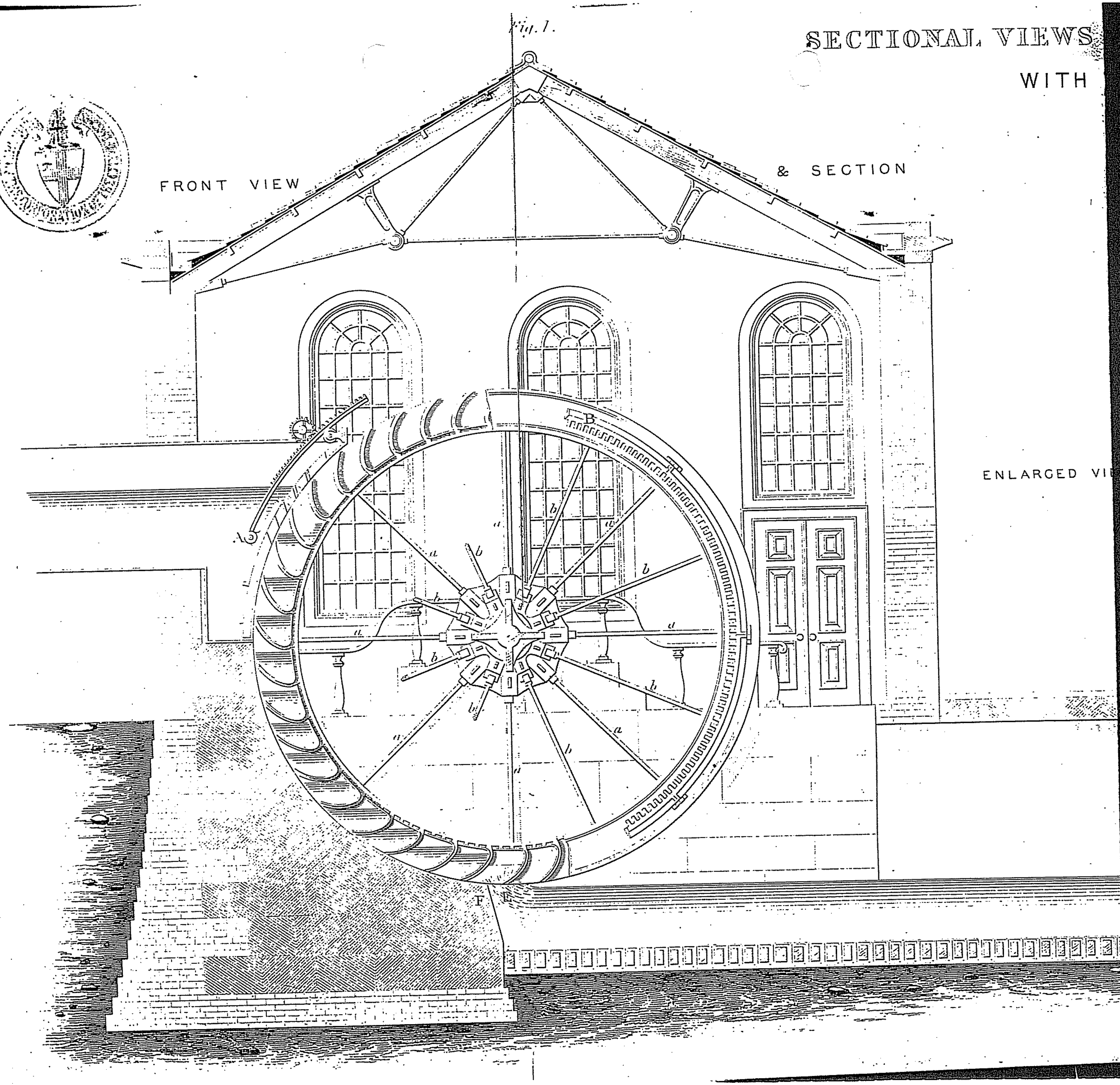

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OF Mr FAIRBAIRN'S IMPROVED WATER WHEEL

VENTILATED BUCKETS & SOLE-PLATE.

AS ERECTED FOR THOS AINSWORTH, ESQR

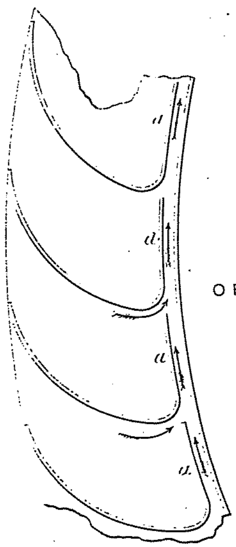
CLEATOR NEAR WHITEHAVEN.

SCALE

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 FEET

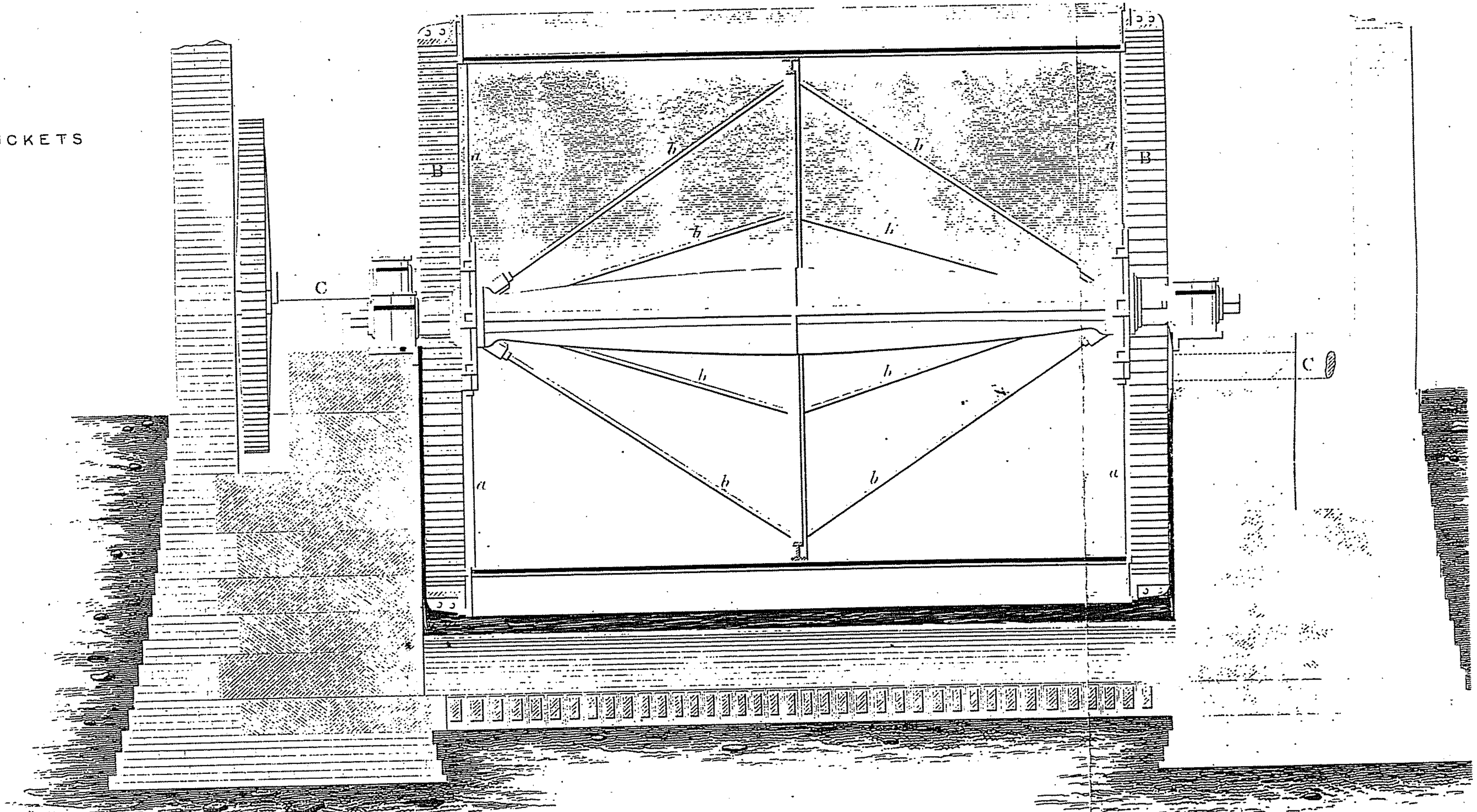
Fig. 3.

W OF BUCKETS



LONGITUDINAL SECTION

Fig. 2.



from the axle, the whole of the force passed through the arms to the point, and afterwards by a pit-wheel by some multiplier of speed to the machinery of the mill. In the improved wheels this is no longer the case: the arms, braces, and axle have only to sustain the weight of the wheel, and to keep it in shape, and the power being taken from the circumference, considerable complexity is avoided, and the requisite speed far more easily obtained.

Speed of Water Wheels.—I have usually made breast wheels for high and low falls, with a velocity between 4 and 6 feet per second at the periphery, and between these limits water wheels may be worked with economy. But for a minimum velocity I have taken 3 feet 6 inches per second, for falls of from 40 to 45 feet, and for a maximum velocity, 7 feet per second, for falls of 5 or 6 feet. The higher velocities, namely, from 5 to 6 feet per second, are now very generally adopted for the best constructed wheels, not indeed on the score of economy in the expenditure of water, but for the purpose of obtaining more easily the requisite speed under the variable conditions of supply. In this climate, where the atmosphere is so much charged with moisture, the rivers, for eight months in the year, generally afford an ample supply of water. It is for this reason that an increased velocity is given to the wheel, in order to increase the power in average conditions of supply, so as to work off the surplus rather than adapt the wheel to the minimum expenditure. It would, however, be advantageous to increase the capacity of the wheel, and work at a velocity of 4 feet, or at most 4 feet 6 inches per second.

Area of opening of Bucket.—The width of the opening of the bucket varies according to the point at which the water is laid on. I have made them with openings as low as 4 inches wide and as much as 20 inches, the first being for very high-breast and the latter for undershot wheels, but ordinarily the width is from 5½ to 8 inches for high-breast and from 9 to 12 inches for low-breast wheels. In this matter the millwright must exercise his own judgment, taking into account, 1st, the quantity of water to be delivered upon the wheel; 2nd, the position on the circumference at which the water is to be delivered, a wider opening being necessary for low-breast than for high; and 3rd, he must consider whether the circumstances of the case in any degree limit the width of the wheel. The width of the opening must be measured perpendicularly to the direction in which the water enters the wheel; thus, in fig. 104, x x is the width of opening.

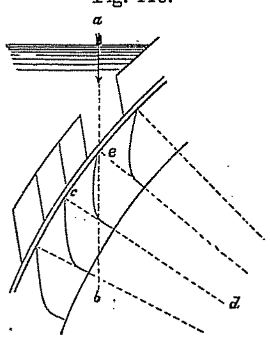
For high falls, the best proportion of the *area* of opening of the bucket, that is, the width multiplied by the length between the shrouds, is found to be such that 5 square feet of sectional area of opening is allowed for 25 cubic feet capacity in the bucket. But in breast wheels which receive the water at a height of not more than 10 degrees above the horizontal diameter, 8 square feet should be allowed for the same capacity. With these proportions the depth of the shrouding is assumed to be about 2 or 2½ times the width of the opening.

The distance of the buckets apart, measured upon the external periphery of the wheel, I have been accustomed to make from 1 foot to 1 foot 6 inches, low-breast being somewhat further apart in general than high-breast. This proportion fixes the number of buckets in the wheel according to the following table:—

		No. of Buckets.
For wheels 10 feet diameter,	from 20	to 30
,, 20 ,,	,, 40	,, 60
,, 30 ,,	,, 60	,, 90
,, 40 ,,	,, 88	,, 120
,, 50 ,,	,, 120	,, 150
,, 60 ,,	,, 130	,, 180

In setting out the curve of the water wheel bucket in breast wheels, a line a b may be drawn cutting the external periphery of the shroud at the point and in the direction in which it is intended that the water shall strike the wheel after passing the guide plates of the pentrough sluice. If we then measure a distance c equal to the distance of the buckets apart, and from the centre e draw the radius d c, the line a b will be nearly the direction of the lip of the bucket and $c d$ the direction of its start, and the curve must be drawn connecting these lines according to the judgment of the millwright, making some allowance for the velocity of the wheel.

Fig. 118.



The Shuttle.—The shuttle of these wheels requires a slight notice. The front of the pentrough is of cast iron, in the form of an arc closely fitting the periphery of the wheel, with an opening extending from side to side for the passage of the water to the buckets. This opening is made of such a breadth and is placed in such a position that when the water in the pentrough is highest it will flow upon the wheel near the top, and when the water is lowest it will still be able to enter the buckets near the bottom. This opening is then fitted with inclined guide plates, arranged so as to prevent the water in entering striking against the sole plate or the back of the succeeding bucket. Over the guide plates is a door, or closely fitting sluice, which slides up or down, according to the height of the water in the pentrough, so as to admit a thin sheet of water flowing over its upper edge through the guide plates into the buckets of the wheel. By this arrangement it will be seen that the water is always drawn off at its highest level and the fall economised to the utmost extent. Racks are fitted to the back of the sluice with pinions, by which its position is altered, and the quantity of water flowing on the wheel adjusted.

In the Catrine wheel, Plates I. and II., the pentrough consists of cast-iron plates bolted together and resting on beams supported on one side by the wall of the wheel-house and on the other on columns.

Figs. 119 and 120 represent the water-wheel governor, a very ingenious arrangement, similar in principle to that of the steam-engine, but adapted in its details to a different purpose. It consists of two heavy balls which in revolving take a position further apart or nearer together, according to the velocity at which they are driven. These balls are swung upon the vertical revolving shaft s s supported in the strong cast iron framing A A A. Two cast iron brackets B B on either side of the frame, and bolted to it, support between them a bridge C C, passing over the driving shaft and clutch box, on which the shaft s s rests in a foot step. This vertical shaft is driven by the bevel wheels F and G, the former of which is keyed on the driving shaft b, which is hollow, to allow the shaft a a connected with the gearing of the sluice to pass through it. A third bevel wheel H, is also placed on a hollow shaft, and is driven by the

Fig. 119.

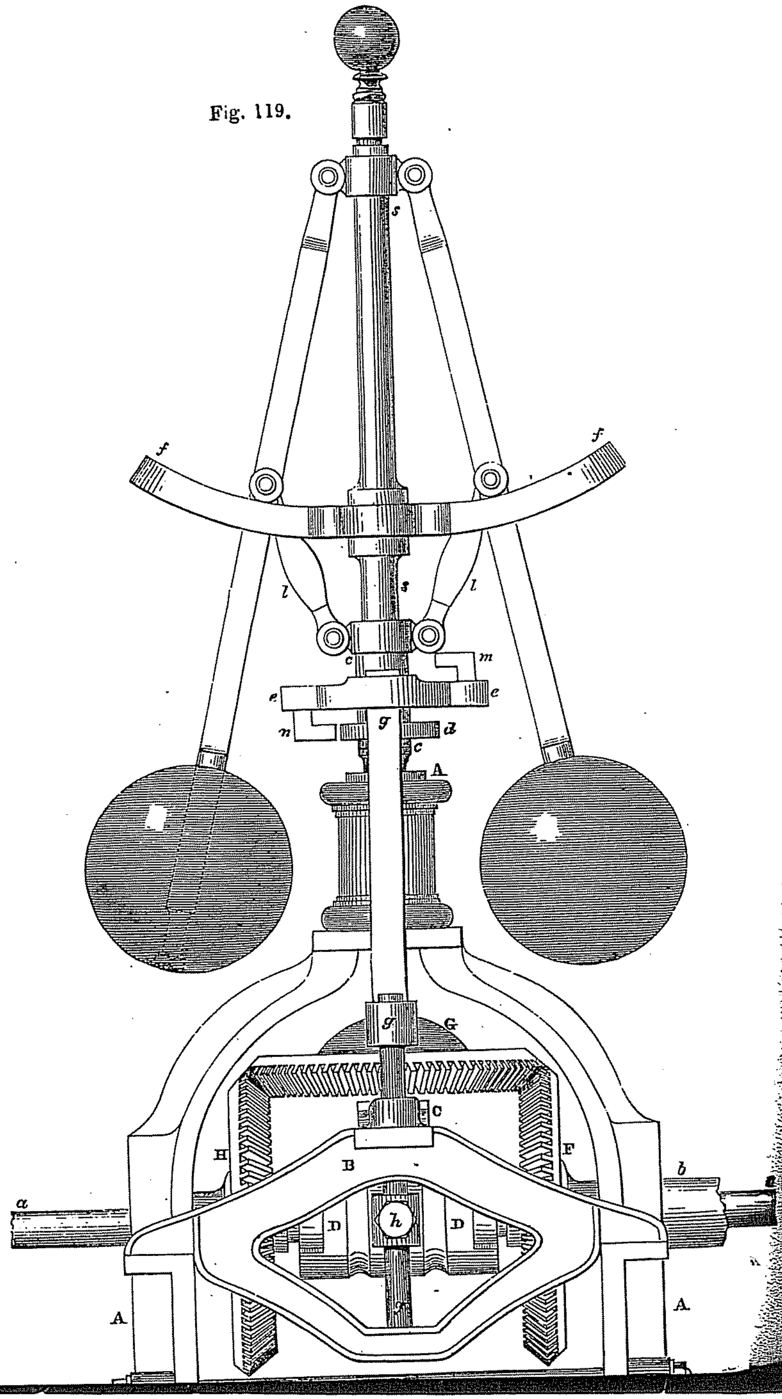
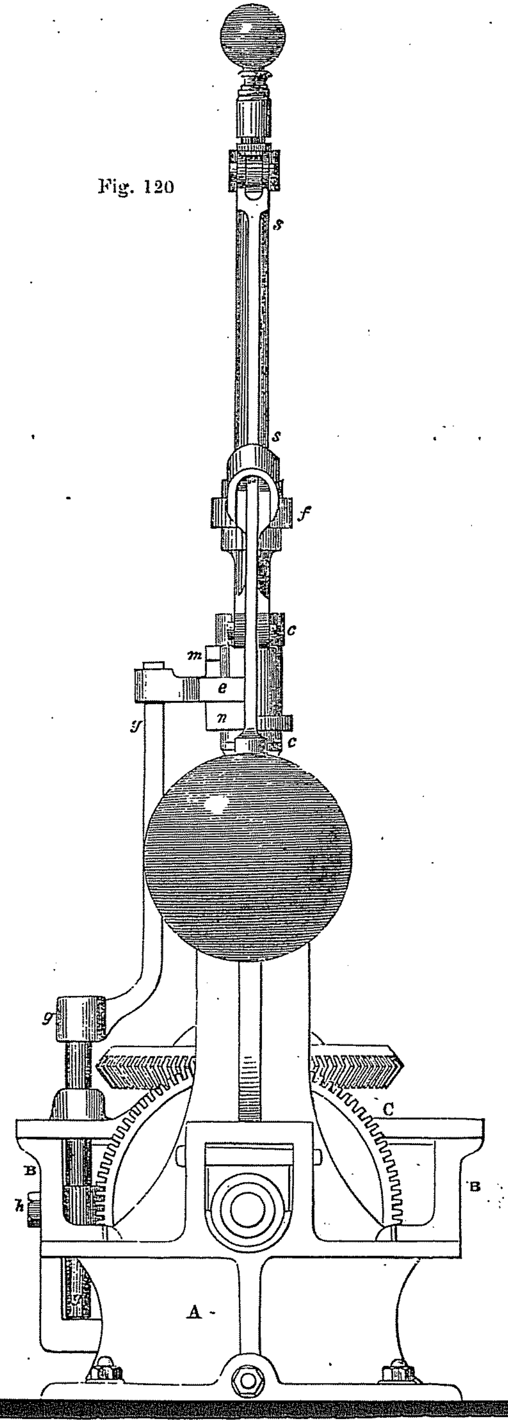


Fig. 120



bevel wheel G, revolving of course in an opposite direction to the first wheel F.

The governor balls with the radial arms and slotted arcs *f f* are of the construction usual in steam-engines, but the links *l l* carry a brass slide *c c*, so that, as the governor balls diverge, this slide is drawn up along the vertical shaft, and as they approach it falls. On the slide is fixed the eccentric cam *d*, shown also in fig. 122 as seen in plan. This cam of course revolves simultaneously with the slide, balls, and vertical shaft *s s*. Attached to the bracket B on one side of the framing is a bent lever *g g g* carrying at its upper extremity a fork *e e*, and near the bottom a similar fork placed vertically, *h*, fig. 121. The upper

Fig. 121.

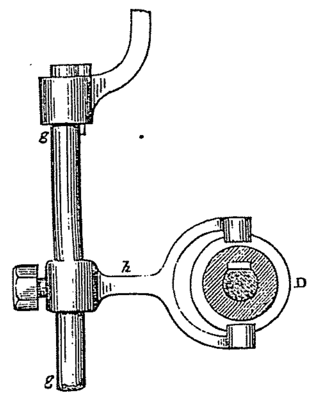
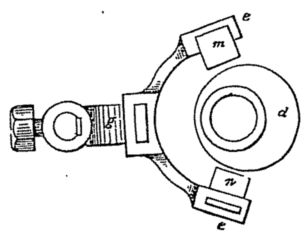


Fig. 122.



fork is moved by the revolving eccentric *d*, the lower fork moves a clutch box which slides backwards and forwards on the shaft *a a*, and engaging alternately with the bevel wheels H and F. When the motion of the wheel becomes too slow the balls fall and bring the cam *d* in contact with a knee of iron *n* in the upper fork *e e*; this causes the clutch D D to be thrown into gear with the bevel wheel H, and the clutch being keyed so as to slide on the shaft *a a*, causes that also to revolve and the sluice or shuttle to be lowered. On the contrary, when the motion of the wheel is too rapid, the balls diverge, the cam *d* is raised and strikes the upper knee *m*; the clutch is then thrown into gear with F; the shaft *a a* revolves in the opposite direction and causes the shuttle to be raised. At other

times, when the motion does not require adjustment, the clutch is disengaged from both wheels and the whole of the winding apparatus is stationary.

This arrangement of governor is exceedingly compact and effective, and a great improvement on the original condition in which I first found it, with rollers and reversing pulleys. It is free from the objection to which those governors are open which directly bring the sluice gearing into operation and retain it so by their momentum.

As examples of the speed at which this part of the machinery is worked, I subjoin a few examples that are working successfully:—

Governor shaft, . . 36 revolutions per minute.
Rack shaft, from 0·0314 to 0·058 revolutions per minute.

There is usually a worm on the shaft *a a*, working into a wheel on a cross shaft; on the cross shaft a second worm working into a wheel on the rack shaft; and a small pinion 8 inches in diameter on the rack shaft gears into the rack upon the sluice. This rack should be jointed to the sluice at the middle, and should be of such a length that the rack shaft and pinion can be placed out of water above the pentrough. But the details of the gearing and shafting by which the motion of the governor is transmitted to the sluice vary with the position of the governor and the circumstances of each particular locality, and they must therefore be left to the millwright's own judgment. Only it is important to observe that the motion of the sluice should in every case be slow, as in the above examples, or the acceleration or retardation in the supply of water will cause an irregular motion first faster and then slower in the wheel, conditions inadmissible where machinery is employed.

In designing a water wheel the first important consideration is the height of the fall; this taken in conjunction with the intended outlay will fix the diameter of the wheel. We must next determine the form of bucket as already detailed. Then the quantity of water per second in cubic feet must be ascertained, and this will determine the necessary capacity of the bucket and the consequent breadth of the wheel. Here we have to consider also, 1st, that the bucket is not to be more than one-third or one-half filled; and, 2nd, the rate of revolution of

TABLE OF PROPORTIONS OF WATER WHEELS.

Diameter of shrouds Ft. in.	Fall Ft. in.	Depth of shrouds in inches	No. of buckets	Opening in buckets in inches	Speed of periphery per second Ft. in.	Diameter of segments Ft. in.	No. of Cogs	Pitch in inches	Breadth in inches	Remarks
60 4	56 4	14	144	3¾	4 0	59 11¾	912	2½	10	External spur.
50 0	48 0	15	120	6	4 1	48 6	560	3¼	15	
46 0	42 0	10	144	4½	4 0	44 6	560	3	10	
46 0	41 10	13	120	4½	4 1	44 7	480	3½	12	
40 0	36 0	18	80	6½	4 2	37 9	432	3¼	14	
39 9	35 4	12	112	5	4 0	39 4	592	2½	8	External spur.
40 0	36 2	10	112	4¾	4 3	38 5¼	480	3	9	
40 0	36 0	18	80	6½	4 2	37 9	432	3¼	14	
36 0	32 0	18	80	7	4 2	33 8½	384	3¼	15	
36 0	31 8	16	80	7	4 4	33 6¼	384	3¼	14	
32 10	28 3	13	96	5½	4 4	30 7½	384	3	9	
30 0	27 0	12	96	5½	4 4	28 9	360	3	10	
30 0	24 0	18	72	7	4 6	28 2	324	3¾	14	
30 6	27 0	15	84	6	4 4	29 0½	364	3	12	
28 6	23 0	18	60	7½	4 6	26 2	300	3¼	13	
28 0	24 9	22	60	7½	4 5	25 1	216	4⅜	14	
26 0	22 8	10	70	5	4 6					
26 0	24 0	18	60	7	4 2	23 8	270	3¼	12	
26 3	22 0	14	70	6	4 4	24 8	310	3	10	
24 0	20 0	14	70	6	4 6	22 4	280	3	10	
24 0	21 0	14	60	6	4 6	22 0	276	3	10	
24 0	20 2	20	48	8½	4 4	22 0	252	3¼	14	
22 9	19 6	8	80	3¾	4 6	21 6½	390	2⅜	6	
22 6	18 10	14	60	6	4 0					
22 3	20 0	14	70	6	4 4					
22 0	20 0	10	70	4¼	4 6	21 10	330	2½	6½	External spur.
22 0	18 3	19	48	7	4 8					
22 0	19 6	19	48	8	4 10	20 3	232	3¼	12	
21 0	17 5	16	50	7	4 7	20 0	250	3	9	External spur.
20 0	17 0	20	48	7½	4 6					

Diameter of shrouds Ft. in.	Fall Ft. in.	Depth of shrouds in inches	No. of buckets	Opening in buckets in inches	Speed of periphery per second Ft. in.	Diameter of segments Ft. in.	No. of Cogs	Pitch in inches	Breadth in inches	Remarks
20 0	16 0	22	40	8	4 4	17 10½	224	3	12	
20 0	17 6	14	56	6½	4 6	18 6¼	232	3	9	
19 9	17 0	10	60	4½	4 7	18 6½	280	2⅓	8	
19 0	16 4	12	48	5	4 10	17 7⅜	264	2⅓	10	
19 0	16 0	22	42	10	5 6	16 1⅞	174	3½	13	
18 0¼	15 0	15	48	6	4 9					
18 0	14 0	20	32	13	5 4					Ventilated.
18 0	15 0	20	32	11½	5 10	16 0	200	3	14	Ventilated.
18 0	15 9	12	48	5½	4 3	16 6	248	2½	8	
18 0	13 4	22½	32	21	6 0					Ventilated.
18 8	15 0	20	40	15½	5 6	16 9	192	3¼	14	Ventilated.
16 6	13 0	24	36	12½	5 6	12 3	132	3½	10	Ventilated.
16 0	10 6	18	40	15	5 6	15 4¼	192	3	12	Floats, ventilated, external spur.
16 0	12 8	15	40	9	4 10					
16 0	14 0	16	40	7¼	5 0	14 0¾	176	3	12	
16 0	12 0	24	32	16½	5 8					Ventilated.
16 0	11 4	21	32	17	6 0	14 0¾	176	3	9	Ventilated.
16 0	12 8	28	32	17	6 4					Ventilated.
16 0	11 9	24	32	15	5 10					
15 6	12 0	20	40	10½	5 8					Ventilated.
15 0	12 0	16	32	10½	5 8	14 6	168	3¼	10	
15 0	13 2	12	40	6	4 8					
15 0	13 0	18	36	7	5 3	13 10	174	3	10	Ventilated.
14 0	10 0	15	36	9	5 6					
14 0	8 6	15	36	9¼	5 10					Ventilated.
14 0	11 8	24	36	4¼	5 2					Ventilated.
12 6	10 0	10	36	4½	5 0					
12 1	8 3	12	30	6	5 1	11 6	174	2½	7	
12 0	8 0	15	36	6¼	5 0	10 10	162	2½	7	
12 0	10 4	8	36	4	4 8	11 3½	282	1½	4½	
10 0	8 0	8	36	3½	4 6					
7 0	5 0	6	32	2⅛	5 0	6 5½	248	1	2½	

the wheel which determines the number of buckets passing the shuttle per second. (p. 140.)

Suppose a wheel, having 5 feet peripheral velocity per second, supplied with 3,000 cubic feet of water per minute, and the breadth of which has to be determined so that the buckets shall be only one-half filled:—

Let depth of shroud = . . . 14 inches
distance between buckets = . . 14 inches
section of water in bucket when full,
at the pentrough = . . . 144 sq. ins.

Here five buckets pass the sluice per second, and each must contain $\frac{3,000}{5 \times 60} = 10$ cubic feet of water per second; but they are to be only one-half filled when containing this quantity of water, hence their capacity must be 20 cubic feet. Their sectional area is 1 square foot, and hence 20 feet is the breadth necessary for the wheel.

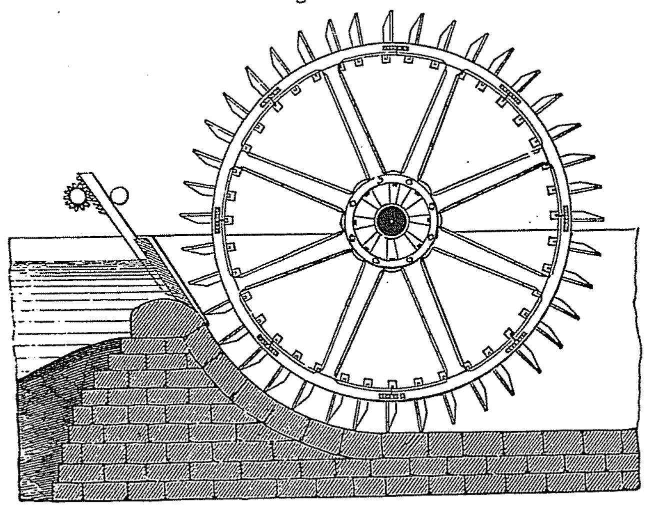
The table on pp. 148, 149, of the proportions of water wheels which I have constructed, may afford aid to the engineer and millwright designing wheels, in their adaptation to different heights of falls, quantity of water, &c.

CHAPTER IV.

ON THE UNDERSHOT WATER WHEEL.

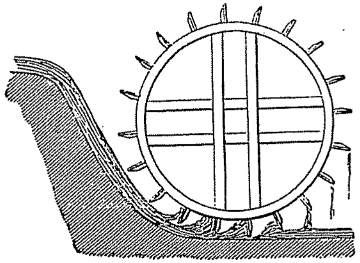
Before the introduction of iron, undershot water wheels were frequently employed, and were in almost every instance constructed with straight radial floats, as in the annexed sketch, the water being discharged against the float boards, as it rushed with considerable velocity underneath the shuttle. This was the invariable practice down to Smeaton's time even, the prin-

Fig. 123.



ciple being to employ the impulse of the fluid stream, and not its gravity or weight. Indeed, there appeared to be an impression that this was the more effective and economical mode of application, and probably arose out of the circumstances of the original employment of water as a moving power. The earliest wheels of which we read are undershot wheels placed between two boats in a flowing stream, and driven by its impulse, and in Smeaton's own time the works for the supply of water to London obtained their power from some magnificent examples of precisely similar wheels, placed in the tidal stream rushing between the clumsy piers of the old London Bridge. In the old time it was no doubt an advantage to have the prime-mover working at a considerable velocity, and an overshot wheel will not do this effectively. Hence wheels were sometimes built of the form shown in fig. 124, the water being carried down from the top of the fall so as to strike the radial floats of the wheel at a very high velocity. Such a wheel is described in Smeaton's reports.

Fig. 124.



The earliest great advance in the perfecting of the water wheel was effected mainly by Smeaton, and we owe to him the first experimental inquiries on the effect and proper velocity and proportions of water wheels. In all the various applications of water, experimental researches have hitherto been the principal means of advance, and in no department has more labour and talent been expended in such inquiries; the result is, that our hydraulic machinery of the present day is as perfect, and yields as high a proportion of the power to the actual fall of water, as we can ever hope to obtain.

In my own practice I have been accustomed to employ water even for very low falls, solely by gravity, using the arrangement already described, as a low breast wheel, when treating of ventilation, and which is shown in detail in Plate III. This wheel is 16 feet in diameter, 17 feet 6 inches between the shrouds, and is adapted to a fall varying from 5 to 8 feet, according to the condition of the river. The water flows into the wheel at its highest level, over a sliding sluice of precisely the same construction as in high breast wheels; it is retained in the buckets to the bottom of the fall, by the cast-iron and stone breast fitting accurately to the edge of the buckets. The advantages of this construction are manifest, as the water expends its full force on the wheel from the very top of the fall, the

buckets being well ventilated, and having a curvature adapted to the position in which they receive the water. By these means, a greatly increased duty is obtained as compared with the wheels with radial floats acted upon by impulse or gravity, or by both. Besides, with this form of wheel, the spider or suspension principle of construction may be adopted, and the power taken off at once from an internal segmental spur-wheel, placed on one of the shrouds, and a high velocity at once obtained, independently of multiplying gear. The advantages of this form of construction in iron wheels are very great, and, when combined with an economical application of the water, they form a machine probably as effective as any which can be employed for falls of not less than five feet.

Radial float wheels, however, constructed of wood are still in use, and the most important directions in respect to these appear to be to make the depth of the floats large, as compared with the thickness of the lamina of water which strikes them; to place the sluice as close as practicable to the floats; to contract somewhat the aperture of the sluice, and to expand the tail-race immediately beyond the vertical plane passing through the axis, to allow the water escaping from the floats to diffuse itself in the tail-race, and pass freely away. These directions, with the following practical formula for fixing the diameter of the wheel, we have from the dissertation on water wheels in the Engineer and Machinist's Assistant.

Let u = the velocity of the extremity of the floats; N the number of turns desired per minute; h=fall in feet. Assume $u = 2{\cdot}4\ \sqrt{h}$ for a maximum effect, then the diameter expressed in terms of the velocity and height of fall will be $19{\cdot}1 \times \frac{2{\cdot}4\sqrt{h}}{N} = \frac{46}{N}\sqrt{h}$ nearly. Thus supposing the height of fall $=h = 4$ feet; number of turns required per minute $= N = 8$; then the diameter $= \frac{46}{8}\sqrt{4} = 11\frac{1}{2}$ feet nearly. Twelve to twenty-five feet is the usual range of diameter for undershot wheels, and the same writer considers 12 to 16 feet to be the most effective; in my own practice, I have found from 14 to 18 feet perform the best duty. Feathering, or inclining the floats, does not appear to increase the useful effect.

The number of floats is usually equal to $\frac{4}{3}d + 12$, where d is the diameter in feet. The thickness of the vein of fluid striking the floats may be from 6 to 9 inches, and the depth of the floats from 18 inches to 2 feet.

M. Poncelet, one of the first authorities on Hydraulic machines, and the first writer on Turbines, has contrived a very important modification of the undershot wheel, which has been used on the Continent with very good effect. A series of experiments led him to the conclusion that the floats should be curved instead of plane, and he deduced that for these wheels the velocity which gives a maximum effect was equal to 0·55 the velocityof the current, whilst it may vary from 0·5 to 0·6. He found the dynamic effect to vary from 50 to 60 per cent. of that of the water, being better for small falls with large openings at the bottom of the flood gate, and less for deep falls with small openings.

For describing the curve of Poncelet's floats, let $c\ c$ be the external circumference, and $a\ r$ the radius of the wheel; take $a\ b = \frac{1}{3}$ to $\frac{1}{4}$ the fall, and draw the inner circumference of the shrouding; let the water first strike the bucket at the point a and in the direction $d\ a$, draw $a\ e$ perpendicular to $d\ a$, so that the angle $e\ a\ r$ will be from 24° to 28°. Take on $a\ e$, $f\ g = \frac{1}{6}\ a\ f$, and from centre g, with radius $g\ a$, describe the curve of the float.

Fig. 125.

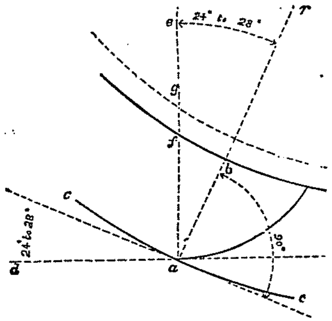
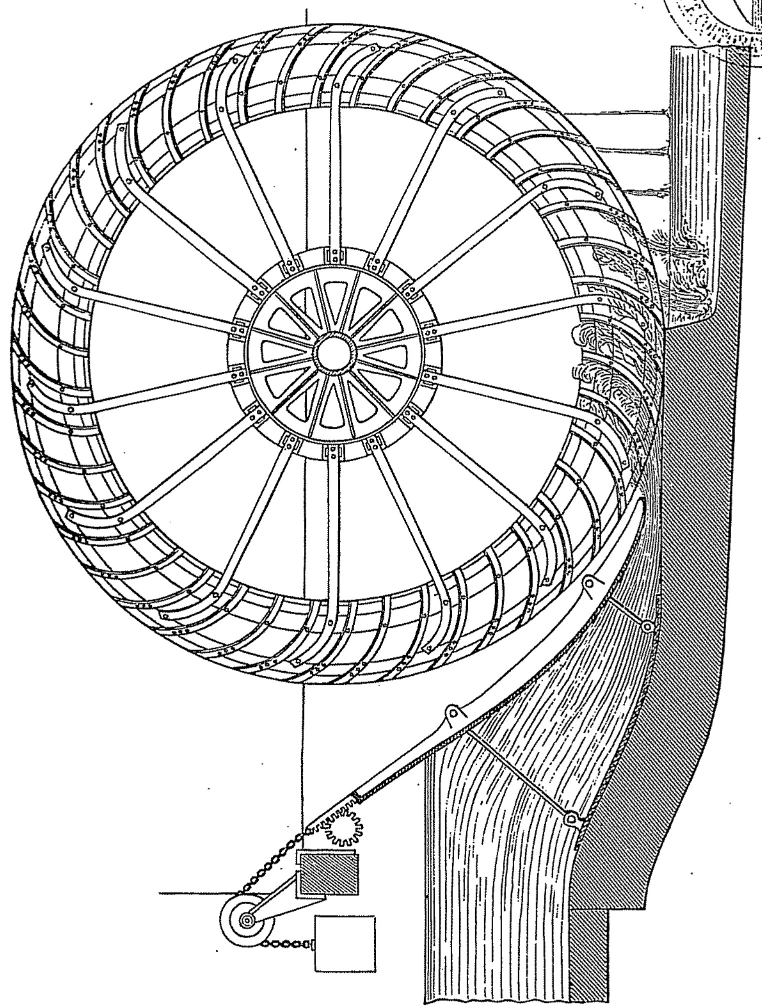


Fig. 126 represents a good example of Poncelet's wheel. The width of the opening should be contracted somewhat towards the wheel so as to assume the form of the fluid vein, and the bottom may be at first inclined $\frac{1}{10}$ to $\frac{1}{15}$ to give the water a greater impetus on the wheel, but over a breadth of 18 or 20 inches at the extremity it should be made to a curve very accurately fitting the periphery of the wheel.

So also the tail-race may be expanded in width and depth to keep the wheel clear of backwater. The buckets are made of

wrought iron of the requisite curve, riveted to the shrouds on each side, and the sole plate is altogether dispensed with; as no resistance is opposed by the air, the buckets are made more

Fig. 126.



numerous than in breast or undershot wheels, and as the wheel carries no weight of water, it may be made comparatively light.

For the number of buckets for wheels of from 10 to 20 feet in diameter, we may take

$$n = \frac{8}{5} d + 16$$

Thus for a wheel 15 feet in diameter,

$$n = \frac{8 \times 15}{5} + 16 = 40$$

The wheel shown in the figure is 16 feet 8 inches in diameter, and 30 feet wide, and is driven by a fall 6 feet 6 inches high, yielding 20,000 cubic feet per minute. With a circumferential velocity of 11 or 12 feet per second, it afforded 140 horses-power.

This wheel gives a useful effect of 50 to 60 per cent. of the water power employed when well constructed, and may be used with advantage for falls not greater than about 6 feet. Above this the low breast wheel is certainly more advantageous and costs less.

Poncelet made some experiments on wheels of this class, with the friction break. The wheel was 11 feet diameter, 28 inches wide, and with 30 floats. He found the efficiency equal to 52 per cent. when the ratio of the velocity of the wheel to the water was 0·52. Morin has also experimented on these wheels, and for falls of from 3 to 4½ feet, with sluice openings of 6, 8, 10, and 11 inches, he found the efficiency 52, 57, 60, and 62 per cent. respectively.*

* In a conversation with General Poncelet on this subject I found that the wheel which bears his name gives a duty of nearly 60 per cent. of the water employed. This is about the same as my own wheel with ventilated buckets for low falls, where the sole is entirely dispensed with. There is, however, this difference, namely, that in the Poncelet wheel the water is discharged upon the floats from *under* the sluice, whereas, in that of the ventilated wheel, it is discharged into buckets *over* the sluice from the upper surface of the fall.

CHAPTER V.

ON TURBINES.

It will be impossible in the present work to enter into details on the theory and construction of the immense variety of prime-movers known under the name of turbines, the development of the principles of which we owe chiefly to continental mathematicians. Two varieties of horizontal wheels or turbines have long been employed on the Continent, which, although ill-devised and ineffective, yet presented evident advantages in their small size, cheapness, and simplicity of construction. These are known in France as *roues à cuves* and *rouets volants*, the former being a small wheel revolving on a vertical axis, and having inclined curved vanes or buckets arranged radially. It is placed in a pit so that the water passing vertically through it should act by pressure and reaction on the buckets. The *rouet volant* differs from this in having the water applied to the wheel at a small part only of the periphery, so as to drive the wheel by impulse. These wheels of from 3 to 5 feet in diameter with nine to twelve buckets are usually made of cast iron, and fixed upon a lever foot bridge, so that they can be slightly raised or depressed. The running millstone is fixed on the upper extremity of the vertical axis, so as to obviate the use of any gearing or belting. In regard to efficiency, the *roues à cuves* yield about 27 per cent. and the *rouets volants* about 30 to 40 per cent. of the water used.

General Poncelet was the first to demonstrate the principle and superior advantages of the turbine, and in 1827 M. Fourneyron recalled public attention in France very forcibly to the construction of the horizontal wheels by a turbine very happily conceived and executed. For this invention he received in 1833 a prize of 6,000 francs; and the principles of his machine