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Sir FREDERICK J. BRAMWELL, F.R.S., President,
in the Chair.

"Water-Motors."

By Professor W. C. Unwin, B. Sc., M. Inst. C.E.

When the Council did me the honour to ask me to lecture on Hydraulic Motors, I could not but feel that they imposed on me a task of some difficulty. The lectures of last year on the applications of steam power related to a matter of pre-eminent national importance, and to one involving some of the most striking and brilliant scientific discoveries of this century. In describing the work of Joule and Rankine and Siemens, the lecturers of last year were recalling names familiar and honoured in this Institution, and discoveries which form the most characteristic scientific advance of recent times.

Water-motors are not now, or in this country, so important as heat-motors, and there is even possibly, among many engineers, an impression that water-motors are at best rather feeble machines, suitable only for small industries. Nevertheless, I believe that even now a much larger amount of water-power is utilized than is generally known, and in circumstances not impossible, or even very improbable, the importance of water-power, even in this country, might be greatly increased. In some by no means very indefinitely deferred period, there must begin to be felt something of the pressure due to the limitation of the coal-supply. No great increase of the price of coal is needed to make water-power much more valuable than it is at present. On the other hand, if the electrical engineer will make the transmission of energy easier, the importance of water-power would also increase, for one of its greatest defects is that it exists in the localities where nature has placed it, and not in the places where it can be most conveniently used.

Numerous isolated cases of the transmission of energy electrically, to do mechanical work at a distance, are no doubt already in successful operation, but in most of these cases the installation has been more or less of an experiment, and the cost has not been greatly regarded. But one case, in which the electrical transmission of water-power has been successfully carried out on a strictly commercial basis, has come under my notice. At Bienne, in Switzerland, the power of a Girard turbine is transmitted electrically a distance of 4,000 feet, and used to drive machinery in workshops. The dynamos are compound wound, and the conductors are carried on posts. A diminution in the cost of electrical apparatus would probably render such cases much more numerous.

The term water-power is convenient, but inaccurate. Strictly speaking, there is no such thing as water-power. Whether the water descends on a water-wheel, or actuates a pressure engine in connection with Mr. Ellington's hydraulic pressure-mains, the water is a mere agent of transmission. In the one case the water-wheel is driven by the energy of gravitation, in the other by the energy developed in a steam-engine; the water merely transmits the pull of gravity or the push of the steam-engine. In neither case is the water itself the source of the power utilized. As we speak of a steam-engine as a heat-motor, so we might speak of most water-motors as gravity-motors.

However, using the term water-power as a convenient one, it may be pointed out that, though a good deal of water-power is already utilized in this country, and though a few motors of very considerable power exist here, it is on the Continent and in America, where coal is dearer, that the most striking instances of the utilization of water-power are to be found. Many members of this Institution have probably seen the turbines at the falls of Schaffhausen, the power of which is distributed to several mills by wire ropes. In the report of the Technical Education Commission there is an interesting account of a visit to Windisch, where 1000 HP. are utilized, the weir and turbines having cost £70,000. At Bellegarde, at the confluence of the Rhone and the Valserine, on a fall of 40 feet, 3,700 HP. are utilized by six turbines, and this amount of power would have been doubled if the project had been commercially successful. Water-power is utilized on a still larger scale in America.

Holyoke and its Water-power.—About 18 miles from the mouth of the Connecticut river there was a fall of about 60 feet in a short distance, forming what were called the Great Rapids, below which the river turned sharply, forming a kind of peninsula, on which the city of Holyoke is now built. In 1831 the first mill was erected and driven by water-power. In 1845, the magnitude of the water-power available attracted attention, and it was decided to build a dam across the river. The ordinary flow of the river is

6000 cubic feet per second, giving a gross power of thirty thousand horses, or in dry seasons probably not less than twenty thousand horses. In a recent exceptional summer it seems to have fallen, for a time, to half this amount. The first weir or dam was completed in 1847, but it was carried away. A second dam was built in 1849, with a base of 80 feet and a height of 30 feet. The dam is a timber cribwork filled with stone, and rests on rock. In 1868 it was found necessary to construct an apron to this weir, 50 feet in width. The whole structure is now 130 feet wide, 30 feet above the river bed, and 1,019 feet in length. From above the weir, a system of canals takes the water to the mills on three levels. The first canal starts with a width of 140 feet, and depth of 22 feet. A second canal, parallel through a distance of a mile with the first, takes the water after passing through the mills, and supplies it to a second series of mills. There is also a third canal, at a different level.

With the grant of land for a mill is also leased the right to use the water-power, and the lease of the water-power is transferred to successive tenants with the lease of the mill. A mill power is defined as 38 cubic feet of water per second, during sixteen hours per day, on a fall of 20 feet. This gives a gross power of eighty-six horses, or an effective power, with a good turbine, of about sixty-three horses. The charge for the power is at the rate of 20*s*. per horse-power per annum. Mr. Emerson, from whom I borrow my data, may well say that Holyoke affords the cheapest manufacturing power in the world.

There are numerous other cases in America where water-power is supplied in a similar way at a cost varying from £1 to £5 per HP. per annum. At Bellegarde, I believe, the proposed charge was £8 to £12 per HP. per annum.

The ordinary source of water-power is a supply of water raised by the sun's heat to a convenient elevation, and falling through natural channels back to the sea. On each pound of water, descending H feet, gravity does H foot-pounds of work. We call H the head due to the elevation, meaning by head the energy per pound of water which would be communicated by gravity during its descent, and which is recoverable by suitable machinery.

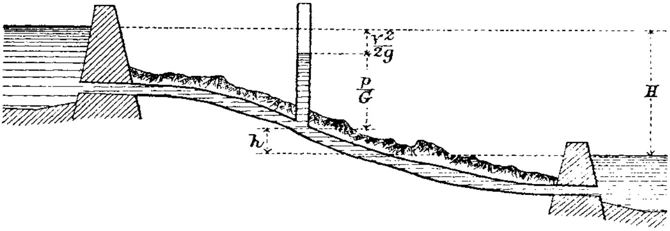
Suppose the water to descend at a uniform rate through a pipe (Fig. 1), which we may imagine frictionless. At any point h feet above the lower level, the water will in general have acquired a pressure p and a velocity v. And in that case we know that

$$H = h + \frac{p}{G} + \frac{v^2}{2g}$$

where h is the unexpended part of the fall, $\frac{p}{G}$ is the energy corresponding to the pressure, and $\frac{v^2}{2g}$ the energy corresponding to the velocity of each pound of water. Consequently the head may take three different forms, and, at whatever point of the pipe we make the examination, these three portions of head add up to the same total amount.

Corresponding to each of these three forms which the head takes there is a class of water-motors. By a bucket water-wheel we can recover the energy corresponding to an unexpended part of the fall; by a pressure-engine we can get the energy due to the pressure, and by a turbine we can get the energy due to the velocity.

FIG. 1.



I. BUCKET- OR CELL-WHEELS.

First, then, there are bucket- or cell-wheels, in which the water fills the buckets near the top of the fall and descends in contact with the wheel without acceleration.

About this class of motors I have time to say very little. They are simple in principle, and have a fairly high efficiency. But they are somewhat cumbrous and antiquated machines. On falls above 70 feet they cannot be used. On falls of 20 to 60 feet a turbine is cheaper, and yields an equal efficiency. On a low fall, if a turbine costs as much, it has, if well-constructed, a higher efficiency. Still in one respect a good overshot or high-breast wheel is superior to most more modern water-motors. Its efficiency is nearly the same with a reduced supply of water as with the full supply. In this respect many turbines, otherwise excellent, compare very unfavourably with the water-wheel. It is probably because many turbines are not so good as they might be, and because many are extremely bad, that the water-wheel is still constructed, for the falls for which it is most suitable.

II. Pressure-Engines.

The second way of utilizing water-power is to bring the water to the level of discharge in a closed pipe at small velocity but with a pressure but little less than that due to the height of fall. The water under pressure acts on the piston of a pressure-engine precisely as steam acts in a steam-engine. There are numerous hilly mining districts, especially in Germany, where water-pressure engines are used. Hydraulic lifts and hydraulic cranes in connection with accumulators are pressure-engines driven by an artificially created head of water.

Now although a water-pressure engine is in certain cases a perfectly successful and economical machine, it is not in most cases the best plan to utilize water-power in this way. It may perhaps be instructive to consider why, almost without exception, we use a cylinder and piston with steam and yet only exceptionally resort to the same expedient with water.

The great difference between steam under pressure and water under pressure is this—that one is a comparatively light fluid indefinitely expansible, the other a comparatively heavy fluid, the volume of which is not measurably changed by any ordinary variation of pressure.

The frictional losses of energy in a fluid are proportional to its weight. If, for instance, water is 500 times heavier than steam, then at the same velocities of flow the frictional losses are 500 times greater in the water than in the steam. To prevent enormous waste of energy in friction, a water-pressure engine must be run much more slowly than a steam-engine, and all the pipes and passages for a given volume of flow must be much larger. A steam-engine has a piston speed of 400 or 500 feet per minute; a water-pressure engine rarely has a speed exceeding 80 feet per minute. Steam flows in steam-pipes with a velocity of 100 feet per second, but in the passages of a pressure-engine the velocity of the water does not exceed 4 to 6 feet per second. Hence for a given power a water-pressure engine is much more cumbrous than a steam-engine, except in those cases where the water-pressure is 8 or 10 times as great as is practicable with steam. It is just when an exceptionally high-pressure can be obtained, or requires to be used, that the water-pressure engine is most applicable.

The second difficulty in the use of water in a pressure-engine arises out of its incompressibility. The same volume of water, and consequently, in most cases, the same amount of energy must be expended each stroke, whether the resistance is great or small. If a hydraulic lift rises, the same volume of water is expended whether the lift is empty or loaded. Where the work is intermittent this disadvantage is often far more than counterbalanced by the other advantages of the use of water. But where the work is continuous the waste of energy is more serious. Suppose a pressure-engine is employed—as it not uncommonly is—in pumping. Then the pressure cylinder must be so proportioned that the work is done when the fall supplying the pressure is lowest and the lift highest. If the fall increases or the lift diminishes no economy of water is realizable, but some prejudicial resistance by throttling must be created to prevent the engine running away and to absorb and waste the surplus energy. Such engines only work with good efficiency with a constant fall and lift, and only then when quite exactly proportioned to the work to be done.

Many years ago Sir W. Armstrong invented the plan of distributing hydraulic power in towns. For doing intermittent work, especially for lifting purposes, the system of hydraulic-pressure mains has proved altogether successful; the most remarkable application being the system of several miles of mains worked at a pressure of 800 pounds per square inch, and successfully laid in the streets of London by Mr. Ellington. Hitherto, however, the system has not proved so useful for ordinary power purposes as was no doubt originally expected. The pressure is too great to be conveniently applied in a turbine, and the pressure-engine in its ordinary form is too extravagant in its consumption of water for ordinary power-purposes.

It has been proposed to admit a variable quantity of water to the pressure-cylinder from the pressure-main, and to complete the stroke with water drawn from a low-level reservoir. The driving effort would then be very irregular, but the plan does not seem impossible. Some years ago Mr. Hastie invented a pressure-engine in which, by very ingenious automatic gear, the stroke of the engine is varied, diminishing when the resistance decreases, and increasing when the resistance increases.

Through the kindness of Mr. Ellington, a drawing is exhibited of an improved "Hastie" engine, which is being introduced for power-purposes in London. The engine has fixed cylinders, on the plan of the "Brotherhood" engine, and the spring gear which alters the stroke is much simpler than in the original engine.

There are other peculiarities in the action of water-pressure engines which arise out of the weight and incompressibility of the acting fluid. In the first place, the whole column of water between the pressure-cylinder and the supply reservoir virtually forms part of the piston of the engine, so that a water-pressure engine is in general an engine with a very heavy piston. The effect of the inertia of the piston is very well understood. It tends to make the effective effort transmitted smaller than the pressure on the piston in the first half of the stroke, and greater than the pressure on the piston in the second half of the stroke. In a steam-engine this is often an advantage. The diminution of steam-pressure, due to expansion, can be in great part neutralised by the effect of the inertia of the piston. At any rate the inertia of the piston generally tends to diminish the inequality of the driving effort. It is otherwise with a water-pressure engine, in which the water-pressure, being constant, the effect of inertia is to render the driving effort variable; and this is so much the less advantageous, because while with the light fluid steam we can neglect the weight of the fluid, with water we must reckon the weight of water in the supply-pipe as forming part of the piston.

I believe that the precise part played by the inertia of the water in the motion of a pressure-engine has first been indicated by Professor Cotterill in his Treatise on Applied Mechanics. He has specially treated of the case of a rotating engine, while I shall consider rather those pressure-engines which make a stroke, uncontrolled by a crank and fly-wheel. In such engines the inertia of the fluid behind the piston tends to produce an acceleration of velocity and shock at the end of the stroke, which in general can only be prevented by means which reduce the efficiency of the engine.

In a very early water-pressure engine of Trevithick's, the piston-valve was made less in length than the width of the port, so that for a short period the supply-pipe was directly open to the exhaust, the flow being gradually arrested by wire-drawing as the valve closed. This involves very great waste. In later engines the valve closes somewhat gradually towards the end of the stroke, so as to retard the flow. But the resistance thus created absorbs and wastes most of the kinetic energy of the water in the supply-pipe.

We diminish the difficulty due to the inertia of the moving mass of water by very much restricting its velocity. It is mainly on account of the inertia of the water that while steam-engines are run at 400 to 600 feet of piston speed per second, water-pressure engines are rarely run at more than 60 to 80 feet per minute.

There are certain cases in which the friction and inertia of the fluid, which in most cases are prejudicial, render essential service in the working of the machine. The friction increasing as the square of the velocity acts as a brake in preventing the velocity from becoming excessive, and the diminution of the effective effort at the beginning of the stroke, and its increase at the end of the stroke, which is due to the inertia of the fluid column, is extremely advantageous in certain operations.

All Members of this Institution will be acquainted with Mr. Tweddell's admirable hydraulic riveting and punching machinery. It is well known that those machines work not only very efficiently in the sense of doing their work well, but they work with a smaller expenditure of power than machines driven by gearing. That is due partly to saving the friction of the gearing, but mainly to the fact that the machines make no waste strokes. They do not keep on running while waiting for work. On the other hand, in the actual working-stroke there is a proportionately large loss of work.

Fig. 2.

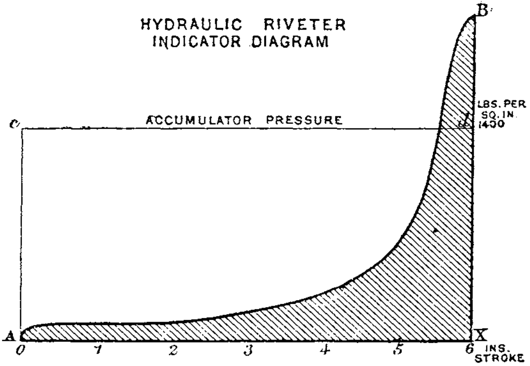


Fig. 2 shows a diagram from a riveter driven by a differential accumulator through 30 feet of 1-inch pipe. The water in the pipe accelerates and is retarded proportionately to the movement of the riveter ram, and the accumulator weight also accelerates and retards in the same way. Hence the water in the pipe and the accumulator weight virtually form part of the moving riveter ram. But as the accumulator weight moves six times as fast as the riveter ram, the forces due to its inertia are thirty-six times as great as if it were attached to and moved with the riveter ram; and as the water moves eighty-one times as fast as the ram, the forces due to its inertia are more than six thousand times as great as if the water moved at the same speed as the ram. In this machine, therefore, the virtual weight of the ram which closes the rivet, and which is put in motion and stopped every stroke, is 300 tons.

To control the movement of such a mass as this, powerful brake-action is necessary, and Mr. Tweddell's brake is supplied by the automatic action of the water-friction.

On looking at the diagram, Fig. 2, it will be seen that the effect of the inertia is to greatly diminish the pressure in the beginning of the stroke, and to increase it above the accumulator-pressure at the end of the stroke. That is advantageous in closing the rivet. But a large part of the diagram is missing; apart from friction and inertia the diagram would be a rectangle A *c d* X. The actual pressure-line falls greatly below this. Fig. 3 shows an estimate of the friction. There are two rectangles, A *a b* X and *e c d f*, showing the uniform friction of the cup leathers of the riveter and accumulator rams, and there is a surprisingly large area *a m k* B *g* representing the friction of the water in the 1-inch pipe. In fact, it

Fig. 3.

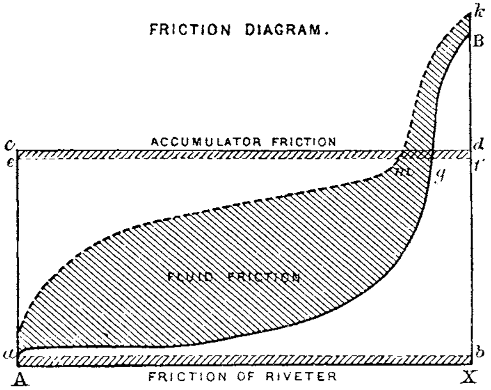
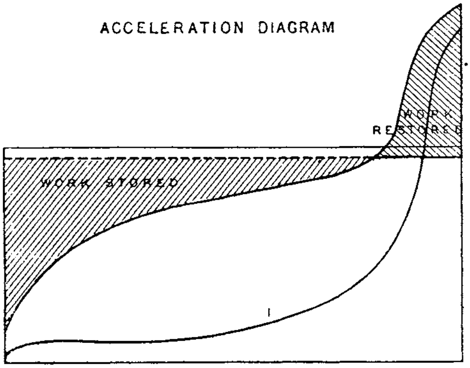


Fig. 4.



is this friction which determines the speed of the machine, and keeps it down to the safe limit of about 1 foot per second at most. When the friction diagram is added to the diagram of useful work, we see that the unbalanced or stored work in the first half of the stroke *a e m* is nearly equal to the excess of work *m k f* at the end of the stroke, so that the machine comes to rest without any violent shock. Mr. Tweddell's riveter is virtually a 300-ton hammer, controlled by a powerful automatic friction brake. Fig. 4 shows better the work stored in the first part of the stroke, and re-stored in the second.

III. TURBINES.

There are motors, of which the undershot wheel is an old type and the turbine a modern type, in which the head is allowed to take the third form before acting on the motor. On undershot wheels and turbines the water acts in virtue of its velocity. Let the water acquire a velocity due to the head in a given direction. Then the water, by its inertia, opposes change of velocity and direction. In the class of wheels now discussed, the water gives up its energy through this action of its inertia. We have now to study under what conditions we can best recover the energy of motion of the water.

Of the whole energy expended by the water on the machine, a part is taken up and utilized, another part is wasted or lost. It is the object of the designer to make the latter part as small as possible, and it is therefore necessary to consider in what ways this loss or waste of energy may arise.

1st. There is a waste of energy if the water is allowed to break up into eddies or irregular motions. When water breaks up in this way we say there is loss by shock.

2nd. The water leaving the machine may carry off with it part of its energy, there is then a waste of unutilized energy. In many motors this loss is a large one. In the class of motors now considered, this energy rejected can be made as small an amount as we please.

3rd. In flowing over the solid surfaces of the machine, there is what is termed fluid or skin friction. This is really a loss of the same kind as that due to shock, because skin friction arises from the production of small eddies against the roughnesses of the solid surfaces, or from instability in the fluid itself.

There are some smaller losses due to leakage, friction of bearings, and so on, which for the purpose of this lecture may be treated as negligible.

Losses due to shock or breaking-up.—If water is poured from a height into a basin, it acquires in falling energy of motion. Reaching the vessel it is dashed about in different directions and broken up into eddying masses. In a short time the friction destroys this irregular motion, and the energy is wasted.

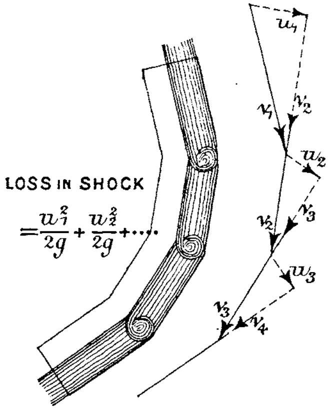
There is generally such a breaking-up of the fluid and waste of energy if the direction of motion or velocity of a fluid stream is abruptly changed.

Let the water be moving along a pipe which changes section abruptly. Then the velocity v_1 in the first part is changed to v_2 in the second. At the abrupt change of section, eddies are continually formed which carry off part of the energy of the fluid in a useless form. The energy thus subtracted from the energy of translation, and for practical purposes lost, is—

$$\frac{(v_1 - v_2)^2}{2g}$$

For example, if the section of the pipe is doubled, the loss of energy is one-fourth.

Fig. 5.



So much for abrupt change of velocity. Next consider abrupt change of direction. To make the problem quite simple, suppose the water flowing round a bent trough A B C D, Fig. 5. At each bend eddies will be formed at the expense of the energy of flow along the surface. Resolve v_1 at A into a component v_2 parallel to A B and a normal component u_1. Then the energy corresponding to u_1 is wasted, and the water proceeds along A B with the velocity v_2. Resolve v_2 at B into a component v_3 parallel to B C, and a normal component u_2. Then u_2 is wasted. Thus for the whole surface, there is wasted for each pound of water—

$$\frac{u_1^2}{2g} + \frac{u_2^2}{2g} + \frac{u_3^2}{2g} + \ldots\ldots$$

Now notice the velocities u_1, u_2, u_3, depend on the angles at the bends, and vanish if those angles are indefinitely small. Hence, if the surface is curved throughout, there is no loss due to breaking up, and the water flows round with its velocity unchanged, except so far as there may be a very small loss due to the friction of the surface.

Hence the second condition for avoiding loss in dealing with streams of water is, that the surfaces over which it flows should be gradually and regularly curved.

Generally in hydraulic motors we have to deal with fixed jets of water impinging on moving curved vanes. The condition of avoiding loss due to abrupt change of direction imposes a third very important condition as to the direction of the vane where the jet first impinges. Let A B be the fixed jet of water, B C the moving vane. Let v_2 be the velocity of the jet, and u the velocity of the vane. Resolve v_2 into a component u equal and parallel to the velocity of the vane, and a relative component v_r. Then if the tangent to the vane at B is parallel to v_r, there is no change of direction when the water first impinges on the vane, and no loss due to eddies or breaking up.

These three conditions—gradual change of section, gradual change of curvature of the surfaces, and the inclination of the receiving edge of the vanes in the direction of relative motion—can always be satisfied, and hence there need be no loss in an hydraulic motor due to the shock or breaking up of the fluid.

The two other sources of loss in an hydraulic motor, the energy carried away, and the skin-friction against the surfaces of the motor, are not so easily disposed of. We can indeed reduce the energy carried away almost as much as we please. If there were no skin-friction, turbines might have any efficiency short of 100 per cent. The energy carried away in good turbines is often not more than 6 per cent. But it might be reduced to 3 per cent. or 1 per cent., only in doing this, we should in general seriously increase the loss from skin friction.

It is this loss from skin friction which regulates the proportions of turbines, and which compels us to use, in many cases, small and high speed turbines on high falls. The writer erected a 70-HP. turbine on 250 feet fall, with a wheel 15 inches in diameter, making 1500 revolutions per minute. The skin friction of the disks of this turbine probably amounted to 4 HP. If the diameter had been doubled to reduce the speed to 750 revolutions, the skin friction would probably have amounted to 16-HP.

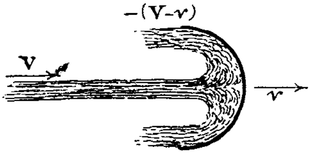
Before considering the more complex case of turbines, it will be convenient to examine one or two simpler cases in which these principles are applied.

Consider first the old form of undershot waterwheel. The water issuing under a sluice with nearly the whole velocity due to the head, strikes the radial floats. There is a loss due to breaking up, and as the water flowing away cannot have a less velocity than the wheel, there is a large amount of energy rejected. Under the best conditions when the wheel has half the velocity due to the fall, 25 per cent. is lost by shock, and 25 per cent. rejected into the tail-race. So that apart from the losses by friction and leakage, an undershot wheel utilizes less than half the energy of the fall.

Many years ago General Poncelet recognized the causes of loss in the ordinary undershot wheel, and constructed the well known Poncelet wheel. I pass over this to examine another less known example of a wheel of this type.

If a jet strikes a hollow cup larger than itself, there is little loss due to breaking up, the jet spreading symmetrically. The water spreads with the relative velocity $V-v$, which is reversed in direction at the lip and becomes $-(V-v)$, so that the absolute velocity of discharge is $-(V-v)+v=2v-V$. By making $v=\frac{1}{2}V$, the water leaves the cup with no energy left, that is all the energy of the jet is expended on the cup.

FIG. 5A.



Now to supply the Placer mines in California, canals or " ditches " have been built high on the slopes of the Sierra Nevada. These deliver water at an elevation of 1000 to 3000 feet above the great valley of California. In many cases the mines have been exhausted or abandoned, and hence has arisen the idea of using the water power, amounting in the aggregate to several 100,000 horse-power, for mills or quartz crushing.

The fall is here excessively great, and if it were attempted to use turbines, especially those forms most in favour in America, there would be the inconvenience that the turbines would run at an immoderate, and in some cases an unmanageably great speed. This has the double disadvantage of involving great wear and tear, and of requiring a large amount of gearing with its concomitant frictional waste.

About twenty years ago there was introduced a form of impact wheel which, with American talent for nicknames, was called the Hurdy-Gurdy. It consisted of a wheel of considerable diameter with a series of cast-iron floats 4 to 6 inches wide on the face. A jet of water of very small diameter (three-eighths of an inch sometimes) was allowed to strike the vanes normally. Theory shows that in this case the wheel should run at half the speed of the jet, and that the efficiency, even apart from friction, could not exceed 50 per cent. Practical experience also showed that the wheel should have half the velocity of the jet, and the efficiency was found by experiment to be 40 per cent. In spite of the low efficiency, such wheels seem to have been useful, partly because they were cheap and free from any liability to accident, but mainly, probably because, by choice of diameter of wheel, any convenient speed of rotation can be obtained.

It is easy to see that the efficiency could be improved by substituting cups for flat floats, and this is what has actually been done. The favourite wheel now is a wheel termed the Pelton wheel, the floats of which are simply cups which deviate the water backwards. A wheel of this kind, working to 107 HP. under a head of 386 feet, is said to have given an efficiency of 87 per cent. Without accepting exactly this figure, I see no reason why, with a very high fall, an efficiency of 80 per cent. at all events should not be reached.

At the Idaho mines, seven of these Pelton wheels have recently been erected to work to about 320 HP., driving machinery previously driven by steam. The water is brought a distance of 9000 feet in a thin wrought-iron riveted main, 22 inches in diameter. The total head is 542·6 feet, reduced by friction in the main to an effective head of 523 feet. The nozzles by which the water is delivered to the wheels are from $\frac{15}{16}$ to $1\frac{15}{16}$ inch in diameter and the power is taken from the wheels by 2-inch Manilla ropes in grooved pulleys. The cost of the change from steam to water-power was between £10,000 and £11,000. The wheels work with hardly any attention or wear, and are believed to give 80 per cent.

THE JET REACTION-WHEEL OR SCOTCH TURBINE.

There is a very simple form of reaction-wheel which forms a convenient step towards a true turbine. In this the water enters the centre of the wheel, spreads radially, and issues in jets tangentially to the direction of revolution. The water issues under the head h due to the fall and $\frac{v^2}{2g}$ due to the centrifugal force of the mass of water in the wheel. Let V be the velocity of the wheel, then the velocity of the water through the orifices is

$$v = \sqrt{2\,g\,h + V^2}$$

and the backward velocity of the water at the jets is

$$v - V \doteq \sqrt{2\,g\,h + V^2} - V$$

It is obvious that this approaches zero as V approaches infinity. For any smaller speed, part of the energy of the fall is rejected into the tail-race in the backward motion of the water. Taking friction into account, the best speed of the wheel is the velocity due to the head, and then about 17 per cent. of the energy is carried away, and another 10 or 15 per cent. is lost in friction.

Now it was the study of the source of the waste of energy in this wheel which led Fourneyron to the invention of the turbine. Fourneyron perceived that in order to avoid the loss due to the backward velocity of discharge, an initial forward velocity must be given to the water. By putting the water in rotation forwards by fixed guide-blades before it enters the revolving wheel, the backward velocity of discharge can be made as small as we please, and then the efficiency of the turbine may approach 100 per cent. as nearly as we please, apart from the frictional losses, which can in no case be prevented.

The Scotch turbine would from its simplicity be still used in certain cases, but for two serious practical defects. One is that it is the most unstable in speed of all turbines; the other is that it admits of no efficient mode of regulation for a variation of water-supply.

At the beginning of this century there existed a number of horizontally rotating water-wheels, driven by jets of water, or by rotating masses of water, which acted on them chiefly by their inertia. The efficiency of these was very low. In some treatises, especially those of Euler, there were indications of the true principles of construction of such a motor. But it was Fourneyron in 1827 who first realized a practical turbine. Fourneyron received the prize of 6,000f. for his invention from the Société d'Encouragement. His turbine is still sometimes constructed with very little modification, and its essential features are present in turbines of all constructions.

Fourneyron perceived that if the water was to leave the wheel without any backward velocity, that is without carrying away and wasting energy, the water must have given it some initial forward velocity before entering the wheel, and his invention mainly consisted in the introduction of guide-blades to give that initial forward velocity.

In the Fourneyron turbine, the water descending into the centre of the wheel is put into rotation by the guide-blades, and passes into the wheel with a velocity rather less than that due to the head. It passes through the wheel radially and outwards, and hence the Fourneyron turbine is called an outward-flow turbine. The great defect of the Fourneyron turbine is the practical difficulty of constructing any good form of sluice for regulating the power of the turbine. With the cylindrical sluice ordinarily used between the guide-blades and wheel, the efficiency falls off rapidly as the supply of water is diminished, and it is this practical difficulty which I think is leading to a general abandonment of the Fourneyron turbine.

The Fourneyron turbine was soon succeeded by the Jonval turbine, in which the water flows parallel to the axis of the turbine. The Fourneyron turbine works best above the tail water. The Jonval turbine has the advantage that it can be placed below the tail water, or at any height less than 30 feet above it with a suction-pipe. But its sluice arrangements are even worse than those of the Fourneyron turbine.

Lastly Professor James Thomson introduced an inward-flow turbine, in which the water flows radially inwards and is discharged at the centre of the wheel. The greatest advantage of this arrangement is that a perfect system of movable sluices or guide-blades can be adopted to regulate the power of the turbine, there being ample space to arrange these outside the wheel.

There are therefore outward-flow, inward-flow, and axial or parallel-flow turbines. To these must be added a form used by the late Mr. Schiele, in which the water flows inwards radially and afterwards axially, the wheel-vanes being prolonged nearly to the centre of the wheel, and which may be called a mixed-flow turbine.

Now in all these turbines, and in all modifications of them constructed for many years, a peculiarity of proportion originally adopted by Fourneyron was followed. Instead of allowing the water to issue from the guide-blades with the whole velocity due to the head, he so proportioned the passages that there was a more or less considerable pressure in the space between the guide-blades and wheel. All these turbines are therefore pressure-turbines, that is turbines in which the water enters the wheel under pressure.

To maintain this pressure properly two conditions are necessary, the wheel passages must be completely filled with the stream of entering water, and consequently the wheel must receive the water continuously over the whole circumference simultaneously. These are therefore turbines with complete admission.

Mr. Girard was the first to perceive clearly the advantage of departing from Fourneyron's practice. Mr. Girard constructed turbines in which the water issued from the guide-blades with the full velocity due to the fall, and therefore with no pressure. The wheel must be placed entirely out of the tail water, so that the issuing water is freely deviated on the curved vanes of the wheel. Nearly the whole energy of motion of the water less the loss in friction is given up to the wheel. Turbines of this kind are called turbines of free deviation or impulse-turbines.

Impulse-turbines may be inward-, outward-, or parallel-flow turbines, but they are very commonly outward-flow. For normal conditions of working they are slightly less satisfactory than pressure-turbines, but they have two very great practical advantages.

In a pressure-turbine there must be a definite rate of flow through the wheel to maintain the exact distribution of pressure in the wheel for which it is calculated. If the guide-blade passages are partially closed the distribution of hydraulic pressure is completely altered, and the efficiency reduced. In the turbine of free deviation, on the other hand, there is no possible change of pressure in the wheel, for it is all open to the air. Each particle of water following the curve of the wheel-vane acts by itself alone without any interference from its neighbours. Hence if the guide-passages are partially closed the stream on the wheel is rendered thinner, but its efficiency is in no way impaired. Hence the regulation of the Girard turbine is in general far more perfect than in a pressure-turbine.

Classification of Turbines.

I.—*Impulse Turbines.*

Wheel passages not filled.
Free deviation.
No pressure between guide passages and wheel.
Discharge above tail-water.
a. Complete admission.
b. Partial admission.
Axial-, inward- or outward-flow.

II. *Pressure- or Reaction-Turbines.*

Wheel-passages filled.

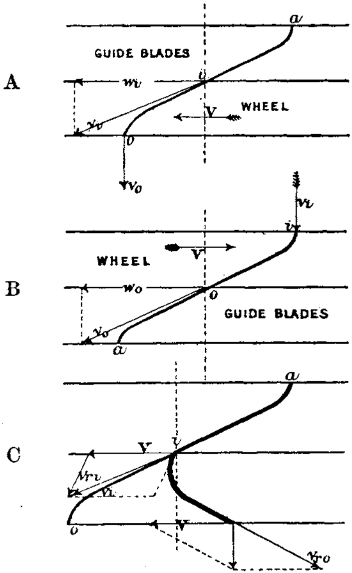
Pressure between guide-blades and wheel.

Discharge above tail-water (outward flow); or below tail water (parallel or inward flow); or into suction-pipes (parallel or inward flow).

Always complete admission, axial, inward, outward, or mixed (inward and downward) flow.

To simplify the consideration of the action of the water in a turbine, suppose that for a turbine wheel moving circularly we substitute a turbine rod moving in a straight line.[1] We can pass to the case of the wheel easily afterwards. To be definite, suppose the water flowing vertically downwards, and the rod (Fig. 6 A) moving horizontally from right to left. To give the initial necessary forward velocity the water must be deflected in some path *a i* by fixed guide-blades. Entering the wheel it produces pressure due to deviation by the wheel vanes, and traverses a path *i o* leaving the

Fig. 6.



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[1] The development of a section of an axial-flow turbine has always been treated in this way, but the use of a turbine rod as the first step in designing any turbine is due to Von Reiche.

wheel finally with a much reduced velocity in a direction normal to the surface of discharge.

A simple application of Newton's second law of motion gives at once the force driving the wheel. The water enters the wheel with the initial velocity v_i, which has the horizontal component w_i, and leaves the wheel with a velocity which has no horizontal component. Each pound of water per second therefore loses the horizontal momentum $\frac{w_i}{g}$, and since impulse is equal to change of momentum, the horizontal pressure on the wheel is

$$\frac{w_i}{g} \text{ lbs.}$$

for each pound per second flowing through the wheel, and the useful work done in driving the wheel is

$$\frac{w_i \, \mathrm{V}}{g} \text{ foot-lbs. per second.}$$

But the whole energy of gravity on each pound of water falling H feet is H foot-pounds. Hence if η is the efficiency,

$$\eta \, \mathrm{H} = \frac{w_i \, \mathrm{V}}{g}.$$

This is the fundamental equation on which the whole design of turbines depends. It gives the relation between the original whirling velocity of the water and the velocity of the wheel.

I stop for a moment to point out that exactly the same result is arrived at if the position of the wheel and guide-blades is inverted as in Fig. 6, B. Then the water having no initial forward momentum gains the momentum $\frac{w_o}{g}$ in the wheel, and the equation becomes

$$\eta \, \mathrm{H} = \frac{w_o \, \mathrm{V}}{g}.$$

In applying this formula the fall H is the effective fall, that is the fall after deducting any losses in the supply-pipe tail-race, &c., which are extraneous to the turbine. From the work η H really utilized by the turbine an additional small loss occurs in the transmission, from friction of the shaft, friction on the wheel covers, and friction of gearing.

It is now to be seen what forms the guide-blades and wheel-vanes must have to direct the water in the absolute path chosen for it.

The guide-blades, being fixed, have exactly the form of the chosen water-paths $a\ i$, Fig. 6, A, or $o\ a$, Fig. 6, B. But the wheel-vanes have a quite different form from the water-path, because as water moves along that path the wheel also is moving.

In order that the water may enter the wheel without shock the first element of the vane must be parallel to $v_{r\,i}$, Fig. 6, C, the direction of relative motion. In order that the final velocity of the water may be vertical the last element of the wheel-vane must be parallel to $v_{r\,o}$, obtained by compounding the final velocity v_o with the velocity V of the wheel. Having obtained the tangents to the two ends of the wheel-vane, any smooth curve joining these two will satisfy the necessary conditions for the proper action of the water.

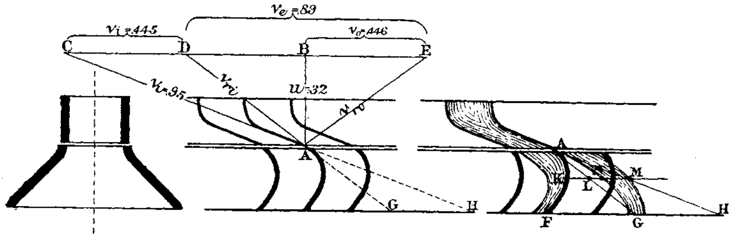
Turbine-Rod corresponding to a Girard or Impulse Turbine.

In the Girard turbine there is no pressure in the clearance space, and therefore the water issues from the guide-blades with the velocity due to the effective fall. In the diagram

$$v_i = 0{\cdot}95\ \sqrt{2\ g\ \mathrm{H}}$$

which allows for the friction of the guide-blades.

FIG. 7. FIG. 8.



Cross-section.

GIRARD TURBINE.

$h = 29{\cdot}5;$

$\sqrt{2}\ g\ h = 43{\cdot}6;$

$\eta = 0{\cdot}89^2 = 0{\cdot}79.$

Next decide what energy shall be rejected into the tail-race. Suppose this is put at 10 per cent., the velocity corresponding to one-tenth of the fall is

$$u = 0{\cdot}32\ \sqrt{2\ g\ \mathrm{H}.}$$

Draw now the triangle of velocities C A B, so that u is the vertical component of v_i. Then C A is the direction in which the water enters the wheel.[1]

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[1] It is assumed here that the velocity of flow through the wheel, u, is constant. If it is not so, the figure must be drawn with the actual values.

Bisect C B in D. Then C D is the proper velocity of the wheel, and A D is the direction of relative motion of the water and wheel, and tangent to the first element of the wheel-vanes.

In an impulse turbine the relative velocity remains unchanged. Set-off B E = the velocity of the wheel, then A E, which obviously by construction is equal to D A, is the direction of relative motion of the water leaving the wheel, and the tangent to the last element of the wheel-vanes.

We have now determined all three angles necessary for drawing the guide-blades and wheel-vanes.

Further, since the relative velocity $v_{r\,i}$ is changed to $v_{r\,o}$ in passing through the wheel, therefore D E or V_e is the velocity utilized in the wheel. Hence the work utilized is

$$\frac{V_e^2}{2\,g},$$

and the efficiency of the wheel is $0 \cdot 89^2 = 0 \cdot 79$, apart from those losses which are extraneous to the turbine itself.

To secure the free deviation of the water on the wheel-vanes, and to prevent the choking of the wheel-passages, it is usual to flare out the wheel as shown in the cross-section. Very commonly the ratio of the inlet and outlet widths is as 4 to 7.

Every datum for the turbine which depends on hydraulic considerations has therefore been determined. And any one who has mastered this very simple diagram, and who has the requisite general mechanical knowledge, can design a turbine, I need not say as well as I could, but as well as Mr. Girard himself could.

In drawing the stream of water on the vane it is merely necessary to remember that the relative velocity is constant, and therefore the thickness of the water-sheet is inversely as the width of the bucket.

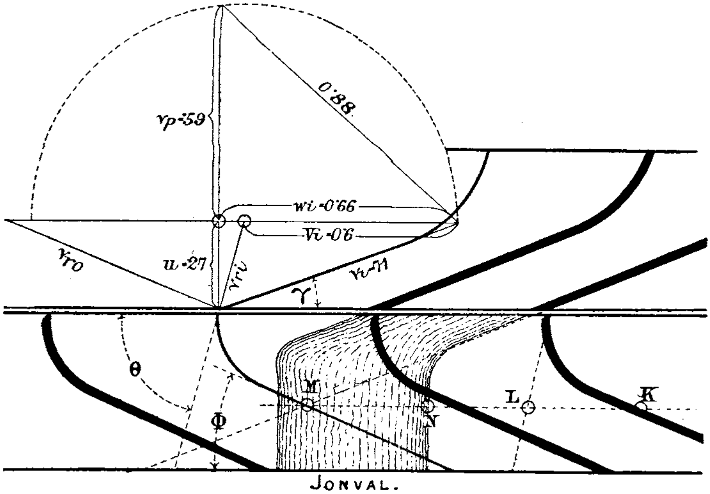
It is useful to examine the exact absolute path of the water in the wheel, which is easily obtained. If there were no wheel-vanes the water would traverse the absolute path A H and the relative path A G. But the wheel-vanes deviate the water the distance L K from A G. Set-off M N = L K, then N is a point in the absolute path. Any number of such points can be found and the absolute path drawn. Or conversely, if the absolute path is chosen the wheel-vane can be drawn. The wheel-vanes will be of good form if the absolute path shows a continuous and tolerably uniform curvature, and if the water-stream through the wheel is a converging rather than a diverging one.

TURBINE ROD CORRESPONDING TO A PRESSURE-TURBINE.

In a pressure turbine the wheel passages are always full. Hence the velocity of flow, that is, the vertical component of the waters' velocity in the diagram is constant, or at all events is determinable from the general dimensions of the wheel. That velocity is, therefore, the velocity at which the water is rejected into the tail race. This ought to be small; it is very often only $\frac{1}{8}\sqrt{2\,g\,H}$, but to make the diagram clearer, I have taken it at $0{\cdot}27\sqrt{2\,g\,H}$, in which case 7 per cent. of the energy is rejected.

Further, 8 to 15 per cent. of the energy is wasted in friction. Taking the extreme case—suppose 15 per cent. wasted in friction; then there remains 78 per cent. to be utilized in the turbine, and the velocity due to 78 per cent. of the head is 0·88 of the velocity due to the head.

FIG. 9.



JONVAL TURBINE.

In a pressure-turbine this 78 per cent. of the energy is partly used in producing the initial horizontal velocity, and partly in producing the pressure in the clearance space. It is optional, how this division is made. In the figure the velocity 0·88 is divided into a horizontal component $w_i = 0{\cdot}66$, and a vertical component $0{\cdot}5v_p = 89$. Hence, if the initial horizontal velocity is taken at $0{\cdot}66\sqrt{2\,g\,H}$, the velocity corresponding to the pressure in the clearance-space will be $0{\cdot}589\sqrt{2\,g\,H}$.

Setting off the assumed vertical velocity 0·27, and the just found horizontal velocity 0·66, we get the initial velocity and direction of motion of the water $v_i = 0 \cdot 71 \sqrt{2\,g\,H}$, and determine the angle γ of the guide-blades.

To determine the proper velocity of the wheel, I shall apply the principle of momentum. As the water enters the wheel with the horizontal velocity $w_i = 0 \cdot 66 \sqrt{2\,g\,H}$, and leaves with no horizontal momentum, the effective horizontal pressure of each pound of water on the wheel is

$$\frac{w_i}{g} \text{ lbs.}$$

and if V is the velocity of the wheel, the useful work done is

$$\frac{w_i\,V}{g} \text{ ft.-lbs. per pound of water.}$$

But 78 per cent. of the energy due to the head is utilized so that

$$\frac{w_i\,V}{g} = 0 \cdot 78\ H,$$

which gives

$$V = 0 \cdot 78 \frac{g\,H}{w_i} = 0 \cdot 78 \frac{g\,H}{0 \cdot 66 \sqrt{2\,g\,H}}$$

$$V = 0 \cdot 6 \sqrt{2\,g\,H}$$

Knowing V and v_i, we have now the direction of relative motion where the water enters the wheel, and the angle θ of the first element of the wheel-vanes.

Similarly combining u and V, we get the relative velocity v_{ro} at the point of discharge, and the angle ϕ at the other end of the wheel-vanes.

It is easy to show that the utilized velocity 0·88 is the chord of a semi-circle, of which the velocity V of the wheel is the radius, so that the velocity of the wheel is easily found graphically and without calculation.

Transformation of the Turbine-Rod into an Inward- or Outward-Flow Turbine.—It is not difficult to proceed by methods similar to those already described to draw directly the path and the curves of the vanes of a radial flow turbine. But the proceeding is complicated by the circular motion, and a more simple method is available. If we draw a turbine rod for any given case first, the corresponding inward or outward flow turbine can be obtained by simple geometrical projection.

Draw circles at the same distances apart as the edges of the guide-blades and wheel in the turbine rod. Subdivide the spaces of the turbine-rod by lines at equal distances, and the spaces of the turbine by corresponding equi-distant circles. Thus let the circle *b* correspond to the line *b* in the turbine rod. Project the point where *b* intersects the wheel-vane to the circle *a*, and draw a radius. Where this intersects the circle *b* is the corresponding point on the wheel-vane curve. The guide-blade and absolute water-path are projected in the same way.

Efficiency of Turbines.—The largest waste of energy in turbines is due to fluid friction, and this cannot be estimated with any great accuracy, and can only therefore be determined by experiment.

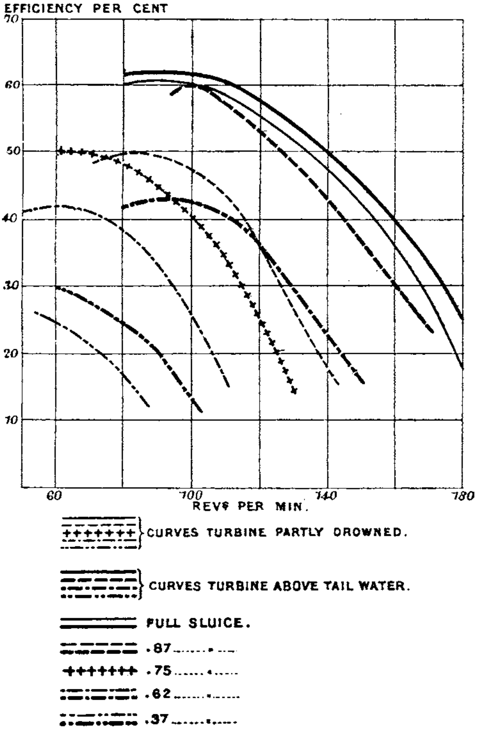
There are a number of experiments, too carefully carried out and too accordant to be put aside, which show that turbines of very different types, well constructed, and working in the best conditions, yield an efficiency little if at all inferior to 80 per cent. A very few experiments, apparently also reliable, show an efficiency slightly greater. But allowing for the probabilities of error in water measurement, I think that 80 per cent. may be taken as the maximum efficiency of the best turbines in normal conditions of working.

While I do not believe that this efficiency is likely in any case to be exceeded, I believe also that any one of the ordinary types of turbine will, within a very small range of difference, yield the same efficiency. The search of inventors, especially in America, for some new modification of the turbine, which shall have a greater maximum efficiency, I believe to be altogether a chase of the philosopher's stone, and not likely to end more successfully than that of the Rosicrucians.

The statements that this turbine or that has attained 82 or 83 or 85 per cent. of efficiency are not only delusive, they are extremely misleading. The probability is that the small extra percentage of maximum efficiency claimed over that of other turbines is due to error of water measurement. But even if this is not the case, the real practical value of a turbine is not measured by its maximum efficiency when everything has been arranged to suit it, but by the average efficiency in the varying conditions of fall, water-supply, speed, and work to be done, in which it has actually to operate. Now there is one condition, at all events, which in most turbines is constantly varying. The supply of water varies either from actual deficiency in the supply, or because the work to be done varies. In either case the quantity of water discharged through the turbine varies. To effect this alteration of discharge, turbines are provided with sluices or regulating apparatus. In nearly all cases the use of the regulating apparatus seriously diminishes the efficiency of the turbine, so that the average efficiency is very much lower than the maximum efficiency. In the mode of regulating different turbines, there are differences far more important than any difference of type or mode of action. Before discussing the efficiency of turbines under regulation, there is a preliminary point to clear up.

Some eighteen years ago I plotted the curves shown in Fig. 10, giving the efficiency of a Fourneyron turbine, with different sluice-openings and at different speeds. There are two sets of experiments, shown by darker and thinner lines, corresponding to the normal condition for a Fourneyron out of water, and to the case where the turbine was partly drowned. Roughly, the greatest efficiency, when the turbine was not drowned, was 62 per cent. with full sluice, 60 per cent. with seven-eighth sluice, 43 per cent. with five-

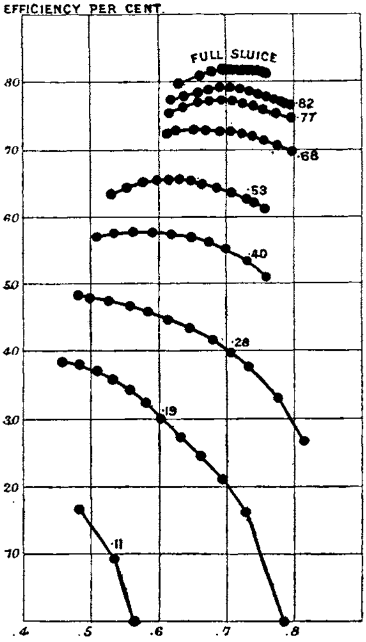
Fig. 10.



eighth sluice, and only 30 per cent. with three-eighth sluice. With the turbine drowned the efficiencies were lower.

For each set of experiments the efficiency is greatest for a given speed of the turbine. But, unfortunately, the speed of greatest efficiency is not the same for different openings of the sluice. With full sluice the efficiency is greatest at about one hundred revolutions. But with three-eighth sluice the efficiency is greatest at sixty revolutions or less. Now, generally the speed of a turbine depends on the work to be done, and cannot be adjusted to suit

Fig. 11.



Speed in fraction of $\sqrt{2gh}$.

hydraulic requirements. If the speed has to vary, as in pumping, with the demand for water, the speed will very commonly differ from that which suits the turbine best, and the efficiency will not, on the average, reach the maximum value. Still more commonly a turbine has to drive machinery at a very nearly constant speed. Naturally, we choose for that speed the speed of greatest efficiency with full sluice. But then for that speed the efficiency falls off much more rapidly with the closing of the sluice than I stated before.

Fig. 11 shows the results of a very extensive series of experiments on the Humphrey turbine, carried out by Mr. Francis at Lowell. The turbine is of 275 HP., on 13 feet fall. The experiments were independent of the manufacturers, and the arrangements for water-measurement and power-measurement were as good as possible. They show the rapid falling-off of the efficiency as the sluice closes, and the diminution at the same time of the speed of greatest efficiency. The fraction of sluice open is printed against each curve.

Fig. 12.

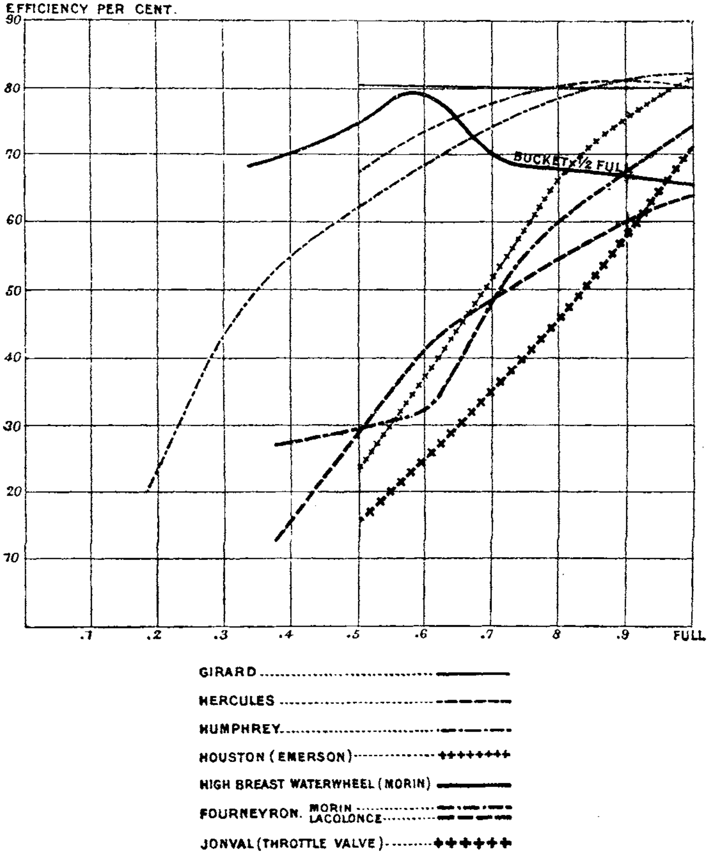


Fig. 12 shows the efficiency of different types of turbine for different openings of the sluice, and always for the speed of greatest efficiency with full sluice, and is intended to indicate the importance of adopting a good method of regulation.

The worst mode of regulation of all, though it is still frequently used, is to put a throttle-valve in the supply-pipe. A throttle-valve acts entirely by creating a prejudicial resistance, or by destroying part of the effective head.

Next worst to this, perhaps, is the form of sluice adopted in the Fourneyron turbine, a circular cylinder which slides in the clearance-space. It is obvious that, when the stream entering the wheel is narrower than the width of the wheel, there must be a general breaking-up of the stream, and a complete alteration of the conditions of pressure and velocity for which the wheel-curves are designed.

The curves for the Hercules and Humphrey turbine show results, I believe, as good as any reliable results obtained in America, the latter being perhaps the most reliable, because the experiment was made by Mr. Francis, whose experience in measuring water by weirs is probably greater than that of any other engineer.

The sluice-arrangements in American turbines do not seem, from the theoretical point of view, particularly good; but although American makers do not explain the principles on which they proceed, I suspect that in these turbines some approach is made towards the condition of free deviation, in which case the defects of the sluice produce a less unfavourable effect.

For pressure-turbines only one approximately perfect mode of regulation has ever been adopted, and that is the movable guide-blades of Professor James Thomson. With this arrangement the water enters the wheel over its whole circumference and depth, with its velocity and direction little changed, in all positions of the guide-blades. The only objection to this mode of regulation is that it involves a certain amount of mechanical complication.

For Girard turbines with partial admission, the mode of regulation is simple, and perfectly complies with theoretical conditions; the width of the stream entering the wheel is altered without in any way affecting the perfect action of the water in the wheel.

On Prince Bismarck's estate at Varzin, three considerable factories worked by turbines have been erected. In the first, in which considerations of capital expenditure were the ruling ones, the turbines were guaranteed to give only 60 per cent.; in the second, 70 per cent.; and in the third, to which I am now referring, the turbines were guaranteed by the makers to give 75 per cent. with full sluice and 70 per cent. with half sluice. If this guarantee was not satisfied, the turbines were to be removed without recompense by the makers. These turbines are Girard turbines; and to ascertain whether the conditions of the contract were satisfied, an extremely careful series of experiments were made, the supervision of which was confided to Professor Zeuner, one of the most distinguished professors of mechanical science in Europe. There are two turbines, each of about 200 HP., on about 12 feet fall. The general result of the experiments was that the efficiency of the turbines was 0·795 with full sluice, and 0·801 with the sluices half-closed, and with the same turbine speed in both cases. These results are the means of four trials in each case, which varied extremely little from one another.

The most careful estimate of the separate losses of work in a turbine which I have met with, is that made by Mr. Lehmann. He has analysed experiments on thirty-six turbines, varying from 1 to 500 HP., and has estimated the average losses of energy from various causes as follows:—

Loss per cent. due to	Axial Flow. Turbine.	Outward Flow. Turbine.	Inward Flow. Turbine.
Hydraulic resistances	12	14	10
Unutilized energy.	3	7	6
Shaft friction	3	2	2
Total	18	23	18
Efficiency	0·82	0·77	0·82

I shall be told—especially by users of turbines in this country—that there are numerous cases of failures of turbines; of turbines which are not giving satisfaction, or which, if they are doing their work, are using an extravagantly large amount of water. There is, no doubt, ground for these complaints; but the reason is not far to seek. Turbines are too often built by manufacturers without adequate hydraulic knowledge. The continued construction of turbines with thoroughly bad systems of regulation is a proof of the want of such knowledge. But most often the turbine fails from quite another cause. No adequate preliminary inquiry is made as to the local conditions in which a turbine is to be placed. Some previously manufactured size of turbine is selected, and put in with very little regard to the precise conditions in which it is to work. The variations of the fall, and the variations of the water-supply, are neither of them determined. Naturally it results that the proportions of the turbine are unsuitable, and the turbine is blamed instead of its constructors.

American Turbines.—There is an opinion in some quarters that the best turbines are now American turbines. I should be sorry to underrate the value of American experience in turbine-building, but on one point I can speak confidently. There is nothing new in principle in any American turbine. The Americans adopted in turn the Fourneyron, the Jonval, the inward-flow, and the mixed-flow turbines, and, so far as I can see, they have copied, without any material change, the turbines of Europe. There are amongst American turbines some so mal-constructed that they look as if they had come from the region behind the looking-glass. Others, no doubt, are excellent; but where they are best they most nearly approach ordinary European patterns. Many American turbines are mixed-flow turbines. This type of turbine is probably the cheapest to construct of all the pressure-turbines, and, like the inward-flow, permits a good mode of regulation. But there is absolutely no advantage in the efficiency to be got by twisting the water round a vane of double curvature, over that which can be got with a vane of simple curvature. In their purely practical aspect, the best American turbines are excellent. They are well manufactured, and attention is paid to designing them so that they can be cheaply erected.

Steam Turbines.—Steam under pressure will work a turbine as well as water under pressure, and with no great alteration in the methods, a steam turbine can be designed like a water turbine. But there is a practical difficulty in the way of the adoption of steam turbines not yet overcome. For steam of, say, 30 lbs. pressure, the height corresponding to the pressure is about 60,000 feet. The velocity due to the head is such that the circumferential speed of the turbine must be about 1,000 feet per second. So soon as we can find a material strong enough and durable enough to stand an excessive speed of that kind, so soon we may have steam turbines much smaller and cheaper, and not less efficient than ordinary steam-engines.[1]

Sir FREDERICK BRAMWELL, President, was quite sure the members had been instructed by the lecture which had been delivered by Professor Unwin. He had dealt with a subject of very great

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[1] The account of the Pelton wheel is from a Paper by Mr. Hamilton Smith in the Proc. Am. Soc. Eng. The Author has to thank Mr. Ellington for drawings of the Hastie engine, and Mr. Gunther of Oldham, Mr. Gilkes of Kendal, Mr. Hett of Brigg, and Mr. A. Rigg, for drawings of turbines exhibited at the lecture.—W. C. U.

importance and of considerable intricacy in a manner which had made it clearer to them than a great deal of study under other circumstances would have done. He had therefore great pleasure in proposing a hearty vote of thanks to the lecturer.

Mr. Woods, Vice-President, said he need not add anything to the remarks of the President in reference to this most interesting lecture, and he would accordingly content himself with seconding very heartily the vote of thanks that had been proposed.

The vote of thanks was unanimously agreed to.

APPENDIX.

SINCE the lecture the Author has received the following additional particulars as to the water power at Holyoke from Mr. Clemens Herschel, the engineer of the Holyoke Water Power Company. They are interesting as showing under what conditions it is possible to distribute water power to different consumers on a very large scale and under equitable working arrangements.

The Holyoke Water Power Company controls the flow of the Connecticut river at Holyoke, on a fall of 60 feet, and having a catchment basin of 8,144 square miles. At this date 15,000 HP. are in use by day, and 8,000 at night, of which part are "permanent powers" held by the parties using them under indentures, and subject to annual rental, and the balance are "surplus powers" held subject to withdrawal at short notice. There are one hundred and thirty-nine water-wheels in use at Holyoke. Observations of the sluice-gate opening and head at each are taken once in the day and once at night, and from these observations the "surplus" power used is calculated and charged for. This system results in economy in the use of water, where otherwise there would be great wastefulness. In times of low water it permits the restriction of the quantity used to the indentured allowance. For experimenting on the wheels before they are erected in the mills, a permanent testing flume has been built. Wheels are tested both as to their power and the quantity of water used. They are tested at five or six different openings of the sluice-gate, ranging from full sluice to the sluice-opening which gives half the full discharge. They are also tested at five or six different velocities for each sluice-opening. The final result is that the turbine is converted into a water-meter, the discharge of which is known for all the conditions of ordinary work. The cost of making the tests is $100 to $150. Tests are also made of wheels sent from other parts of the States. During three years one hundred and eighty-five wheels have been tested.