

## ELEMENTS OF DESIGN FAVORABLE TO SPEED REGULATION IN PLANTS DRIVEN BY WATER POWER.

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In this paper the writer will endeavor to describe those peculiarities of design of plant which have a special bearing on speed regulation, but no attempt will be made to discuss the theory, mechanical construction or merits of the various water-wheel governors on the market.

The engineer is often confronted with the problem of designing a plant upon an undeveloped or partly developed water power, and the desired end is to come out with a plant of good mechanical and electrical design and yet have it such that the speed of the electrical apparatus may be maintained within comparatively close limits under any load variations which can possibly occur, and to maintain the speed within very close limits under any working load variations.

The kind of generating apparatus used, and the nature of the load, predetermines the degree of regulation which must be obtained under both accidental and working conditions, but it is quite evident that the tendency in modern plants is in the direction of apparatus which requires closer speed regulation, and more facility in handling the speed than heretofore.

It is quite possible to obtain on the market, water-wheel governors which will,—provided the design of plant is good,—give quite as good a speed regulation as could be obtained if the plant were driven by first class steam engines.

There is more than one water-driven electric plant in this country where auxiliary steam plants are used, in which the speed is fully as constant while the load is carried by the water-wheels as while it is carried by the steam plant. The plants of the Derby Gas Co., the Pawtucket Electric Co. and the Woonsocket Electric Co. may be referred to as examples illustrating the above fact.

The largest accidental load variation which can occur is evidently an instantaneous change amounting to the full capacity of the water-wheels. The working load variations may be anything less than this.

The writer has found, in a practice amounting to something over 90,000 horse power of water-wheels in the last four years, that with good water-wheels properly set and rigged, and controlled by governors of suitable design, the speed may be held within five or six per cent. of normal upon circuit breakers opening under full load, and that the speed may be brought back to normal in from five to fifteen seconds, depending upon the amount of kinetic energy in the rotative parts and moving water column. With incandescent loads of the ordinary type, a recording tachometer will show a practically straight line. With ordinary electric railway loads, speed variations of about three per cent. as a maximum may be expected. These figures are not intended to be of universal application, but are for simply showing the present state of the art. It should here be added that governors can be obtained which will permit any number of independent water-wheel units driving electrical units connected in parallel, to be operated with perfect convenience and safety. It should also be noted that in the case of alternating units it is perfectly easy to get them at speed and in step for multiple connection without undue delay, and without any hand regulation.

These desirable ends cannot, however, be obtained to their fullest extent if the general design of the hydraulic portion of the plant is bad. We will now consider those things, aside from the governor itself, which tend to make the regulation good or bad.

As a preliminary thought let us consider for a moment that the problem is quite different from steam-engine governing, which naturally comes to the mind in this connection, for the reason that water is heavy, practically non-compressible or non-expansive, and must be transmitted to the water-wheel in large

volume and at low velocity; while steam is light, highly compressible and expansive, and may be transmitted to the engine in small volume and at high velocity. From this it follows that the engine valves are small, light and may be perfectly balanced, while water-wheel gates are necessarily large, heavy and are frequently,—although often unnecessarily,—out of balance. The inertia of the steam may be always neglected; the inertia of the water must be always considered.

The problem of governing a water-wheel, then, involves moving large volumes of a heavy, practically incompressible fluid acted on by the force of gravity alone, and of moving ponderous gates; and this must be done with absolute precision and great promptness. Also adequate provision must be made for the momentum and inertia of the moving water and mechanical parts.

To put our minds in a proper attitude to approach this subject, let us refresh our memories in regard to some of the relations of force, mass, velocity and time.

We have here a mass free to move. Its property of inertia prevents its moving until some force is applied to it. When, however, I apply for a moment the force of my hand it begins to move, and when I stop pushing it, it continues to move with a fixed velocity until I apply to it the same amount of force I used to put it in motion which brings it to a rest, and it cannot move again until a new force is applied to it.

I have here a pendulum beating seconds, and here, (Fig. 1) are two masses consisting of pairs of balanced weights suspended by fine wires over pulleys which have as little friction as possible. One of these masses is twice as great as the other. If we apply to them equal forces in the shape of small additional weights we will find that at the end of one second the smaller mass has acquired twice the velocity of the larger mass; or, in other words, where forces are equal the rates of acceleration are inversely proportional to the masses.

But now I have here two equal masses (Fig. 2) and if we apply to them two forces,—one twice as great as the other,—we will observe that at the end of one second, the velocity of the mass acted upon by the larger force is twice as great as that of the mass acted upon by the smaller force; or, in other words, where masses are equal, the velocities are proportional to the forces.

Now, I have here two masses, (Fig. 3) one twice as great as the other, and if we apply to the larger mass a force twice as great as that which we apply to the smaller mass, we will observe that at the end of one second, their velocities are the same; or, in other words, for equal velocities, the forces must be proportional to the masses.

Or, to generalize; velocities are inversely proportional to masses, and directly proportional to forces.

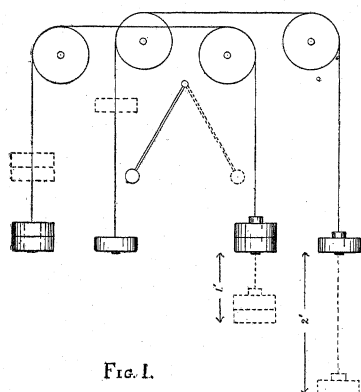


FIG. 1.

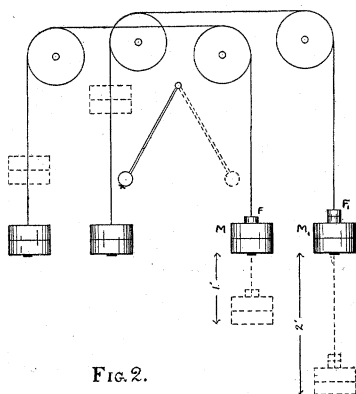


FIG. 2.

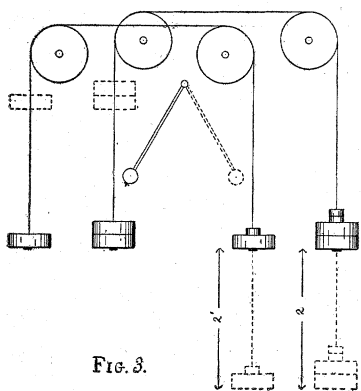


FIG. 3.

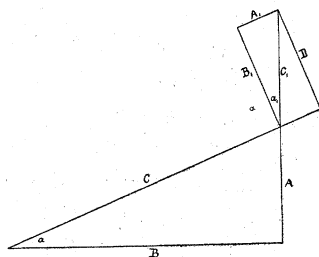


FIG. 5.

Or, by assuming the unit of force as that force which will, in unit time, give unit mass unit velocity, we may formularize the phenomena we have observed, by writing

$$\text{Force} \times \text{Time} = \text{Mass} \times \text{Velocity} \quad (1)$$

from which we may get by transposition

$$\text{Force} = \frac{\text{Mass} \times \text{Velocity}}{\text{Time}} \quad (2)$$

$$\text{Time} = \frac{\text{Mass} \times \text{Velocity}}{\text{Force}} \quad (3)$$

$$\text{Mass} = \frac{\text{Force} \times \text{Time}}{\text{Velocity}} \quad (4)$$

$$\text{Velocity} = \frac{\text{Force} \times \text{Time}}{\text{Mass}} \quad (5)$$

The product of "force" into "time" is called "impulse," and the product of "mass" into "velocity" is called "momentum"; the equation teaches us that an "impulse" is equal to the "momentum" which it produces.

It is chiefly with the practical application of the laws we have just enunciated that we have to do in regulating the speed of water-wheels.

Let us examine still further into the matter. We know that if we let any weight fall freely under the force of gravity,—or, as it is usually written, with a force =  $g$ ,—at the end of one second it will have acquired a velocity of approximately 32.2 feet per second; or, if we throw any weight up with an initial velocity of 32.2 feet per second, the force of gravity will stop it in one second.

In the latter case, the velocity at the start = 32.2, and the velocity at the end of the second = 0, and the mean or average velocity and the distance it will travel =  $32.2 \div 2 = 16.1$  in the first second. Therefore, the work in foot pounds, which any weight can do by being thrown vertically with an initial velocity of 32.2 feet per second = weight  $\times \frac{g}{2}$  feet.

Please note that in above case, the initial velocity ( $V$ ) =  $g$  or 32.2, and that  $V \div g = 1$ .

If, however, we have thrown the weight upward with an initial velocity twice as great as before: *i. e.*, 64.4 feet per second, the force of gravity would stop it in two seconds; but the mean velocity in this case is  $64.4 \div 2 = 32.2$ , which is twice what it was before, and we must also note that it was traveling upward twice as long as before; hence, by doubling both the velocity and the length of time, it will ascend four times as far. Thus, by doubling its  $V \div g$ , which in the latter case = 2, we have enabled the weight to do four times the work. Or, we may truthfully state that in the second case the work equals that in the first case multiplied by  $(V \div g)^2$ ; or, formulating it

$$\text{Work in foot pounds} = \text{weight} \times \frac{g}{2} \times \left(\frac{V}{g}\right)^2 \quad (6)$$

$$\text{Work in foot pounds} = \text{weight} \times \frac{g}{2} \times \frac{V^2}{g^2} \quad (7)$$

$$\text{Work in foot pounds} = \text{weight} \times \frac{V^2}{2g} \quad (8)$$

or we may more conveniently write it

$$\text{Work in foot pounds} = \frac{\text{Weight}}{g} \times \frac{V^2}{2} \quad (9)$$

which is the form in which we will have occasion to most often use it.

As this is a universal law applicable to any force and any velocity it is applicable to water falling under the influence of gravity.

To fix it in our minds let us apply it numerically to the masses with which we have been experimenting. Start with the masses as shown in Fig. 2.

Let the masses  $M$  and  $M_1$  be equal, and let them each be numerically equal to 1. Let  $F = 2$  and  $F_1 = 4$ . Let their time of action  $T = 1$  second, then their velocities at the end of the time  $T$  will be

$$V = \frac{F T}{M} = \frac{2 \times 1}{1} = 2$$

$$V_1 = \frac{F_1 T}{M_1} = \frac{4 \times 1}{1} = 4$$

Now at the end of the time  $T$ , stop the action of the forces  $F$  and  $F_1$  and apply to the masses  $M$  and  $M_1$  in an opposite direction a new force  $F_2 = 2$ . This new force will stop the masses in the following lengths of time:

$$T_1 = \frac{M \times V}{F_2} = \frac{1 \times 2}{2} = 1$$

$$T_2 = \frac{M_1 \times V_1}{F_2} = \frac{1 \times 4}{2} = 2$$

But the space  $S_1$  and  $S_2$  through which they will travel before they stop will be

$$S_1 = \frac{V T_1}{2} = \frac{2 \times 1}{2} = 1$$

$$S_2 = \frac{V_2 T_2}{2} = \frac{4 \times 2}{2} = 4$$

or the masses are as	1 : 1
and the forces applied to them are as	2 : 4
for lengths of time which are as	1 : 1
which give them velocities which are as	2 : 4
and cause them to travel through spaces	
which are, during time $T$ , as	1 : 2
consequently doing work on them which are as	

$$\left(1 \times \frac{2 \times 2}{2}\right) : \left(1 \times \frac{4 \times 4}{2}\right) \text{ or as } 2 : 8$$

They can then oppose equal forces

through spaces which are as	1 : 4
during lengths of time which are as	1 : 2
consequently doing amounts of work which are	
as $FS$ and $FS_1$ or $(2 \times 1) : (2 \times 4)$ or	2 : 8

In the above case the masses  $M$  and  $M_1$  should consist of weights of 32.2 lbs.; that is, the weight at each end of the wire should be 16.1. The force  $F = 2$  lbs.,  $F = 4$  lbs.,  $F_2 = 2$  lbs. A pendulum 39.1 inches long from center of weight to point of support will beat near enough seconds for ordinary experimental purposes. A few experiments carefully carried out with the apparatus shown in Figs. 1, 2 and 3 will teach one more about the relations of mass, force, time and velocity than can readily be learned in any other way.

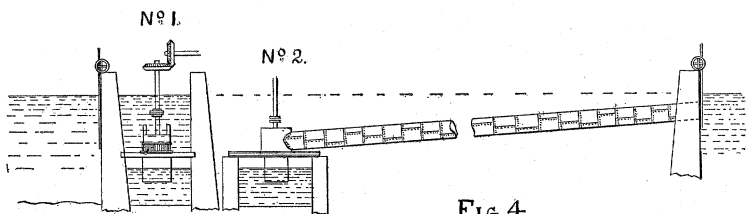
We are now prepared to see the application of the laws, and the formulæ we have written, directly to one of the most important details connected with the installation of water-wheels. This can be best shown by an example.

We have here two water-wheels (Fig. 4) operating under the same head, which we will assume to be nine (9) feet. You will observe that although the head is the same in both cases, one wheel,—which we will designate No. 1,—is set in an open flume of ample size; while the other wheel,—which we will designate as No. 2,—is in a closed flume connected to open water by a long

closed pipe which is nearly horizontal. The behavior of these two wheels when operating under variable load, is entirely different.

Let us assume, for the purposes of argument, that the efficiency of the wheel is the same at all stages of gate, and that the amount of water which passes through the wheel is proportional to the gate opening, and that the power of the wheel is proportional to the amount of water which passes through it under constant pressure. Now, if the wheel is operating at full gate and half the load is suddenly thrown off, and the suitably designed governor attached to the wheel promptly shuts the gates so that only one-half as much water can pass as when the wheel was at full gate, it is evident that the speed will remain comparatively constant.

Let us see if this will be the case with wheel No. 2. If it is operating at full load, and half the load is instantly thrown off, and the governor promptly shuts the gates so that only half as



much water can pass, it is evident that the velocity of the water in the closed pipe must be reduced one-half.

If we assume that the water in the pipe weighs 1,000,000 pounds, and has a velocity at full head of four feet per second, its energy (see formula 9)  $= 1,000,000 \div 32.2 \times 4^2 \div 2 = 248,440$  foot pounds, and if the water velocity at half load is two feet per second, then its energy  $= 1,000,000 \div 32.2 \times 2^2 \div 2 = 62,110$  foot pounds, and the difference between these two amounts of energy,  $248,440 - 62,110 = 186,330$  foot pounds, must be expended upon the water-wheel before the water velocity is reduced to two feet per second.

If it were expended in one second it would  $= 186,330 \div 550$  horse power, but this is a little quicker than we would expect to do in practice. Suppose we slow up the water column in two seconds, then the energy expended  $= 186,330 \div 550 \times 2 = 169$  H. P. for two seconds. The above value of H. P. would not hold strictly true unless the rate at which the gate closed was pro-



portional to the rate at which the water column slowed up; but the total foot pounds expended on the wheel would be as above stated. To find the exact value of H. P. at any instant of time, would require a more elaborate mathematical treatment of the problem than the time now at our disposal permits; but the significant fact to which I wish to call your attention is that this work done upon the water-wheel in slowing up the water column, is entirely independent of, and in excess of, the work which is expended upon the water-wheel when it is working normally at half gate, with the water column moving at a fixed velocity.

It is evident that the above amount of work done upon the wheel while the water column is slowing up, would tend to make the speed of the water-wheel run high if the governor only half closed the gates. In fact, the governor would have to set the gates much nearer closed than one-half; or, to speak more accurately, the governor would, at each instant of time, have to hold the gates at such a position that the power developed by the wheel, due to the working head plus the instantaneous value of power being developed by the slowing water column, equalled the load upon the wheel.

This might be found to be quite unfeasible, for the pressure developed on the closed pipe and wheel case might be dangerous, or the gate might be too ponderous or too badly rigged to permit of the requisite promptness of motion.

The maximum pressure which would be developed at any instant of time at the water-wheel, would be an impossible thing to calculate without knowing a great deal more about the venting areas and time-ratio of closing them than can ordinarily be found out in practice. All that can be predetermined is what may be called, for want of a better term, the time-average pressure. This can easily be determined as follows:—

Let  $P$  = the time average pressure

$L$  = the length of the closed flume in feet.

$V$  = the water velocity in feet per second.

$T$  = the time in seconds in which the water velocity is arrested.

$K$  = the area of a square inch expressed in square feet = .00694.

Then

$$P = \frac{K \times 62.4 \times L \times V}{32.2 \times T} \quad (10)$$

It will be observed that

$$\frac{K \times 62.4}{32.2} = .01324 \text{ is a constant, call this } K_1$$

and the formula becomes

$$P = \frac{K_1 \times L \times V}{T} \quad (11)$$

Applying this to the flume we have been discussing in which

$$L = 300$$

$$V = 2$$

$$T = 2$$

we have

$$P = \frac{.01324 \times 300 \times 2}{2} = 3.97$$

As a water column one foot high exerts a pressure of .43 lbs. per square inch, it follows that a pressure of 3.97 lbs. per square inch represents a head of  $3.97 \div .43 = 9.2$  feet. In other words, if the pressure on the wheel could have been kept constant all the time the water column was slowing up from four feet per second to two feet per second, the wheel would have been working under  $9 + 9.2 = 18.2$  feet of head, instead of under 9 feet of head as it should have been.

From experience we know that it is impossible to close the water-wheel gates at such a rate as to keep the pressure constant, and as a matter of fact, during some portion of the two seconds the water pressure would have been greatly in excess of 3.97 lbs. per square inch above normal, with a correspondingly large disturbance of the speed.

We may note a curious fact in this connection. With a water-wheel set like No. 2 in Fig. 4, working at nearly full gate, and if under these conditions a large portion of the load is instantly thrown off and the governor is of unsuitable design and does not compensate for the kinetic energy of the slowing water column, it may be found by experiment that the speed will run higher than though there were no governor at all. This is for the reason

that for an interval of time the wheel is working under light load and a greatly increased head, and there is, consequently, a greatly increased speed; or, we may say that the amount of energy applied to the wheel under the increased pressure, even though the gate areas have been somewhat reduced by the governor, is greater than would have been the case had the gates not been moved at all.

The first remedy which suggests itself is to place large relief valves near the wheel case, so that they will open and let the water escape if the water much exceeds the static head. This would help matters somewhat upon load suddenly going off, but would it help matters upon load suddenly going on? Let us examine this matter.

Suppose the wheel is working at half load with the water column moving at a rate of two feet per second, and the whole load is instantly thrown on the wheel. The governor will promptly open the gate wide, but the water-wheel cannot develop its whole power until the water column has attained a velocity of four feet per second. To gain this extra two feet per second the water column must have expended upon it the same amount of work which it expended in losing its two feet per second, namely, 186,330 foot pounds, and this must be deducted from the work the wheel will do normally at full gate; so that the instantaneous value of power developed by the wheel while the water column is gaining velocity would equal the normal power of the wheel at full gate minus the instantaneous value of power being expended upon the water column in getting up to speed.

It is evident that the speed of the water-wheel would fall considerably below normal and there would be absolutely no remedy for it in the present state of the art. I say this advisedly and have not forgotten the question of fly-wheels, which is undoubtedly in all of your minds at the present moment.

Let us now consider how long it will take the water column to get up to speed. First let us look again at wheel No. 1 for a moment. We know that the velocity of water falling without friction may be expressed by the formula.

$$V = \sqrt{2g \times H} \quad (12)$$

where  $V$  = velocity in feet per second.

$g$  = 32.2

$H$  = head in feet.

taking  $2g$  outside of the square root sign we have

$$V = 8.025 \sqrt{H} \quad (13)$$

This is the velocity with which water should enter the water wheel.

For purposes of simplicity I have in this paper ignored the corrections which should be made for water friction on surfaces and in orifices, as they do not alter to any large extent the stubborn facts we are considering. Such corrections are beyond the scope of this paper.

Applying formula No. 13 to wheel No. 1 and assuming that the water enters the wheel without friction we have

$$\left. \begin{array}{l} \text{Velocity of water entering} \\ \text{wheel under 9 foot head} \end{array} \right\} = 8.025 \sqrt{9} = 24 \text{ ft. per second.}$$

Now, as the time required for a falling body to acquire a given velocity  $= \frac{V}{g}$  we find in the case of wheel No. 1.

$$\left. \begin{array}{l} \text{Time in seconds for water to} \\ \text{acquire spouting velocity into} \\ \text{wheel under 9 foot head.} \end{array} \right\} = \frac{V}{g} = \frac{24}{32.2} = .7 \text{ second.}$$

Thus, if the gates being closed were instantly opened, the water would be doing its full amount of work on the wheel in seven-tenths of a second.—To make the above absolutely true it would be necessary to assume that the water would enter the wheel with equal freedom at all stages of gate, which is not the case, but it is sufficiently near the truth for our present argument. We are also ignoring what is known as the velocity of approach for reasons previously stated.

To make sure that our figures are right let us calculate the value of  $V$  from our fundamental equation (No. 5.)

$$V = \frac{F T}{M}$$

Assume a vertical water column of one sq. ft. area and 9 ft. high. Its weight is  $62.4 \times 9 = 560.7$ : this  $= F$ .

Then

$$V = \frac{561.6 \times .7}{\frac{561.6}{32.2}} = 22.6$$

which is a close approximation to the value of  $V = 24$  previously

found, the slight discrepancy being due to the fact that 62.4 is not the exact weight of a cubic foot of water, and 32.2 is not the exact value of  $g$ . It might also be added that the square root of  $2g = 8.025$  which is usually given in books on hydraulics, and which was previously given in formula No. 13 is a trifle too large, and a closer approximation to truth will be obtained by calling it 8.02. By using better values we can bring out  $V = 23.8$

Now, in case of wheel No. 2 the water will behave in an entirely different manner. We know that the spouting velocity at wheel No. 2 is the same as at wheel No. 1 minus the friction of the pipe. Unfortunately, we are concerned not only with the spouting velocity at wheel No. 2, but with the length of time it will take to attain spouting velocity at wheel No. 2. The water, instead of falling vertically as in wheel No. 1, runs down an almost horizontal inclined plane. A large part of the force of gravity is applied perpendicularly to the inclined plane and the small remainder is applied to shove the water down the inclined plane. A diagram will make this clear.

Let  $A$  in Fig. 5 = the head in feet from open water above the entrance to the flume to tail water level.

Let  $B$  = the horizontal distance in feet from entrance to flume to draft tube at tail water level.

Then  $C$  = the hydraulic slope.

Project  $C_1 = A$  = the hydrostatic head.

Draw  $D$  perpendicular to  $C$ .

Complete the parallelogram.

Then the force  $C_1$  (which we must remember is the hydrostatic head) is equal to the forces  $A_1$  and  $D$  of which the latter is wholly sustained by the reaction of the plane  $C_1$  while  $A$  is wholly effective in accelerating the motion of water down the slope  $C$ . We evidently wish to know the value of  $A_1$  in terms of the triangle  $A B C$  which is similar to the triangle  $A_1 B_1 C_1$ .

We know that  $A_1 = C_1 \sin \alpha_1$ . Then as  $C_1 = A$  and  $\alpha_1 = \alpha$  it follows that  $A_1 = A \sin \alpha$ . Let us designate the value of  $A_1$  so found as  $f$ .

We have seen (Fig. 3) that the time to give equal masses equal velocities is inversely proportional to the forces.

Calling  $T$  the time to acquire spouting velocity down  $A$  and  $T_1$  the time to acquire spouting velocity down  $C$  we may write

$$T : A = f : T_1 \quad (14)$$

from which we get

$$T_1 = \frac{T A}{f} \quad (15)$$

Let us apply this equation 15 to the case of wheel No. 2 in Fig. 4.

The head

$$A = 9 \text{ feet.}$$

Assume

$$B = 298.7 \text{ feet.}$$

Then

$$C = \sqrt{9^2 \times 298.7^2} = 300 \text{ feet.}$$

$$\text{Sine } a = \frac{A}{C} = \frac{9}{300} = .03$$

$$A_1 = A \text{ sine } a = 9 \times .03 = .27 = f$$

$$A = 9$$

$$T = .7 \text{ previously found}$$

then

$$T_1 = \frac{T A}{f} = \frac{.7 \times 9}{.27} = 23.3$$

seconds required for water to acquire spouting velocity down slope  $C$ .

It may be noted that

$$T_1 = \frac{T A}{f}$$

may be written

$$T_1 = \frac{T A}{A \text{ sine } a} \quad (16)$$

which by cancellation becomes

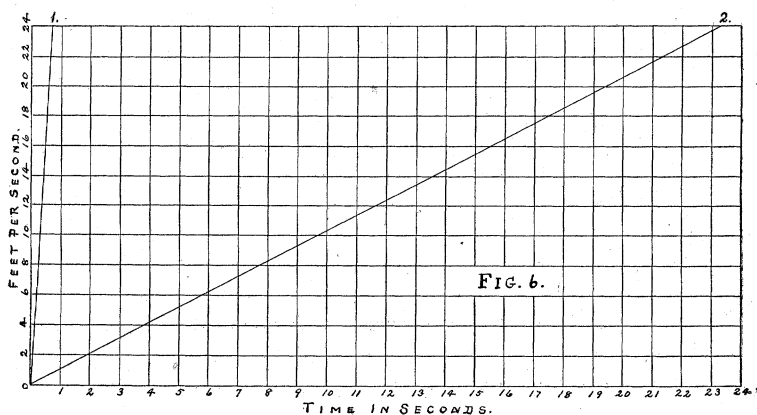
$$T_1 = \frac{T}{\text{sine } a} \quad (17)$$

which is its simplest form, and in which it should be used.

To make the above reasoning plainer, I have plotted (See Fig. 6) lines showing the time necessary for water to acquire spouting velocities into the two water-wheels shown in Fig. 4. Line 0-1 shows the time for water to acquire any velocity up to spouting velocity into wheel No. 1; line 0-2 shows the time for water to

acquire any velocity up to spouting velocity into wheel No. 2.

It naturally occurs to one in this connection, that the water never has occasion to acquire spouting velocity in the flume of wheel No. 2: in fact, we assumed that the maximum water velocity in this flume was only four feet per second, which is only one-sixth of spouting velocity. It can be shown mathematically, and experiment proves that this does not interfere with the line of reasoning we have been following. If, instead of the end of the flume being wide open, it were five-sixths closed, the remaining sixth being an orifice (the venting areas of the water-wheel) capable of being varied at will, it would simply mean that in the flume the value of  $g = 32.2$  would be considerably reduced. This new value we should calculate and call it  $G$ . We could then substitute it for the value of  $g$  we have been



using in our calculations, and the ratio of velocity and time in the open flume of wheel No. 1 and in the closed flume of wheel No. 2 would be found to be the same that we have already ascertained.

But it may be argued that we are concerned with the force which the water will apply to wheels No. 1 and No. 2 while the water is getting up to spouting velocity, and not with the velocity of the water itself. Let us see at what rate the water will develop its full amount of energy on the two wheels we have been considering.

The theoretical amount of energy which flowing water can apply to an obstacle, advantageously placed in its path, may be expressed as follows:—

$$P = F + F = 2 W \frac{V}{g} = 4 w a \frac{V}{2 g} \quad (18)$$

where  $P$  = the theoretical energy developed

$F$  = the force of impulse and also of reaction

$W$  = weight of water flowing per second

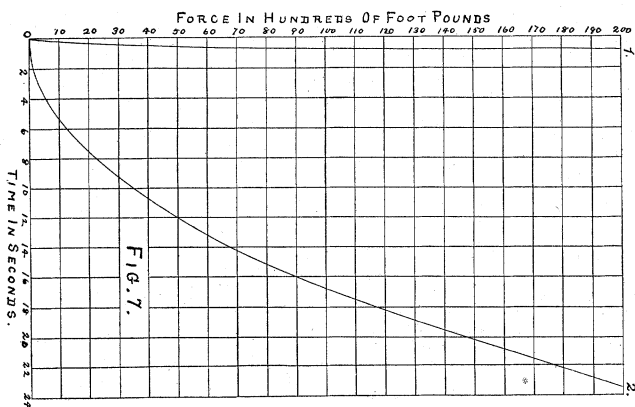
$w$  = weight of one cubic foot of water

$a$  = cross-section of the stream in square feet.

It will be noted that if we assume  $a = 1$ , we may regard

$$\frac{4 w a}{2 g} = 3.9$$

as a constant, which, multiplied by the square of the velocity of flow in feet per second, will give the theoretical force which the water will develop. I have calculated the force developed at



wheel No. 1 and No. 2, as shown in Fig. 4, for each tenth of a second, beginning with the water at a rest in both cases and ending with spouting velocity, and have plotted the values in Fig. 7. Curve 0-1 shows the rate at which water standing at a rest, develops its full energy on wheel No. 1: curve 0-2 shows the rate at which water standing at a rest develops its full energy on wheel No. 2. You will note in the case of wheel No. 1, how very promptly the energy gets to its maximum value, and in the case of wheel No. 2, how the energy lags for a considerable time before it arrives at anything like its maximum value.

I wish to emphasize this line of reasoning, because it is, perhaps, the most important thing to be considered in setting water-wheels where speed regulation is a desideratum. We can,



in an imperfect way, provide for the expenditure of the energy necessary to slow up a water column, but there is no way to make a water column, while gaining velocity, do the work it is capable of when it has arrived at full velocity.

The important fact to which I want to especially call your attention is that the difficulty is measured not only by the length of the closed flume, but is inversely proportional to the sine of the angle of hydraulic slope. When the sine becomes 1; that is, when the angle is  $90^\circ$ ,—or in other words, when the closed flume is vertical,—then the difficulties due to the fact that water moves slowly under the influence of gravity, have reached their minimum and the speed regulation will be the best obtainable. As the sine of the angle of hydraulic slope grows less, then the obtainable regulation grows worse.

There is one way in which the difficulties attendant upon a small angle of hydraulic slope may be in a measure compensated for, and that is by means of a stand pipe.

In an electric plant, it is not usually of such importance that a load change amounting to the full capacity of the wheels be followed by a small speed variation, as that the comparatively large loads which go off and on for short intervals of time shall not disturb the speed to any great extent. Here is where the stand pipe is of value. If a portion of the load goes off instantly, and the correctly designed governor promptly closes the gates to the correct position, the excess of water will flow out over the top of the stand pipe and the water velocity in the flume will not be arrested so promptly as though there were no stand pipe; neither will the pressure at the wheel be much increased. To obtain these results, the stand pipe should be only a very little higher than the water level in the pond. It should be located as near the wheels as possible, and its top should be turned over so that the escaping water can be led to some convenient point of discharge.

If, after a load has gone off instantly, it comes on again in a short interval of time, it finds the water velocity in the flume but little diminished, and also the vertical water column in the stand pipe is ready to apply its energy to the water-wheel in the most advantageous manner. To make the last factor of much practical use, the cross-section of the stand pipe must be sufficiently large to prevent the level of the enclosed water column from falling much while the water in the closed flume is gaining

its lost velocity. As a general statement, the larger the diameter of the stand pipe and the less its height above the hydrostatic level, the better will be the speed regulation. There has not, as yet, been sufficient practical experience with stand pipes to formulate rules which will solve the least diameter which will result in any desired degree of speed regulation.

In the writer's experience, it has been found that the use of a stand pipe of ample proportions will render a plant governable within very close limits under ordinary operative conditions which had proved to be utterly ungovernable before the stand pipe was installed.

From what has been said above, it will be seen that a stand pipe is chiefly of use in aiding a good governor to maintain a comparatively constant speed under those frequently recurring load changes which obtain in electric plants,—especially in electric railway and power plants. It also gives perfect protection against dangerous water pressures being developed when circuit breakers open, or when, for accidental reasons, it is necessary to shut down the water-wheels instantly.

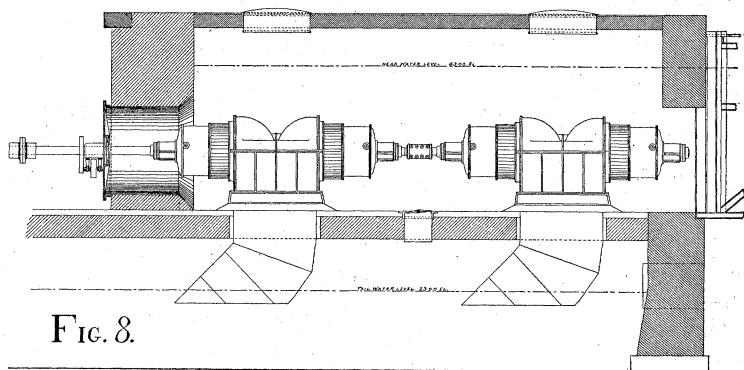
A stand pipe will not,—unless of very large diameter,—enable a good governor to maintain a good degree of speed regulation if the load be increased from friction load to full load instantly, where the angle of hydraulic slope is small, unless such increase of load takes place before the water in the enclosed flume has lost much of its velocity.

The writer had intended to refrain entirely from submitting designs showing the proper setting of water-wheels, for the reason that such a large number of typical plans would be required to cover all probable cases, that it would be hopeless to treat the subject properly without extending this paper beyond proper limits. He cannot, however, resist the temptation to introduce at this point, one design (shown in Fig. 8) which has proved to be singularly adapted to the demands of water-power driven electric plants. It will be noted that the wheels are arranged for direct connection. The angle of hydraulic slope is practically  $90^\circ$ , giving the best possible conditions for speed regulation. The governor may be placed directly outside the flume head and connected to the gates in the simplest possible manner. The speed variations of the main shaft may be transmitted to the governor by one belt. The requisite R. P. M. may be obtained by varying the diameter and

number of wheels. The number or size of wheels on the one shaft may vary from one to as many as can be handled by one governor, or as may be required by the capacity of the electrical unit. This general design has found favor in a number of the most prominent plants in this country as well as in Europe. The regulation is invariably good if a suitable governor be used.

It is usually the case that part of the head utilized in modern plants is below the water-wheel in the shape of a draft tube: in fact, where horizontal wheels are used, it is practically necessary to have them a number of feet above tail water level for convenience of connection to the driven machinery.

The same general rule holds good in regard to draft tubes, which, we have found, applies to closed flumes. They should be as short and as nearly vertical as possible. The maximum



vertical length of a draft tube is, of course, limited by the atmospheric pressure. The water stands in the draft tube for the same reason that mercury stands in a barometer. The specific gravity of mercury is 13.6: that is, it is 13.6 times as heavy as water. Atmospheric pressure holds mercury up in the barometer tube,—let us say 30 inches or  $2\frac{1}{2}$  feet,—therefore it will hold water up in the draft tube  $2.5 \times 13.6 = 34$  feet: that is, it would do so if the draft tube were air tight. The external atmospheric pressure at the top of such a draft tube would be 14.7 pounds per square inch. There are few draft tubes that would stand that pressure without leaking air. This fact is well recognized by hydraulic engineers, and it is rare to find draft tubes 25 feet high from tail water level to water wheel centers. If the water-wheel is likely to be subjected to large load varia-

tions, it is very desirable that the draft tube should have a much less vertical height for the following reason :—

At the bottom of a 25-foot vertical draft tube the atmospheric pressure is forcing the water up with a pressure of 14.7 pounds per square inch, and the weight of the water is pressing down with a pressure of 10.75 pounds per square inch: that is, the difference between the air pressure and the weight is  $14.7 - 10.75 = 3.87$  pounds per square inch. Now, if the water velocity in the draft tube is suddenly arrested by shutting the water-wheel gates the kinetic energy of the slowing water column will be found in the downward momentum of the water. This may easily create a downward pressure greater than 3.87 pounds per square inch, in which case a vacuum would be formed in the upper part of the draft tube and the column of water would sink in the draft tube and immediately after would rush upward again striking the bottom of the wheel with great violence. If we were so fortunate as to escape an accident of the kind above described we should find that with a draft tube of considerable height there is a tendency for air to leak in, and this, under the negative pressure of the weight of the water, expands into a partial vacuum so that the draft tube will be only partly filled with water, and as the position of the water-wheel gates varies as the load changes, the water column in the draft tube will sway up and down producing the effect of a pulsating head on the water-wheel. This is very detrimental to good speed regulation, and is a very common annoyance encountered in practice. The performance of such a draft tube may be easily illustrated by holding a mercurial barometer in the hand and slowly moving it up and down.

Air chambers on flumes, to give protection against water hammer effects, are of very little practical use unless of ample size, even if they are full of air. The writer examined a plant so located that the bursting of the flume would have destroyed the whole plant and ruined an investment of, at least, \$100,000. At the lower end of the flume was a large air chamber. The superintendent in charge pointed with pride to it, and confidently expressed the belief that it afforded ample protection against the dangerous strains on the flume due to water hammer. Upon examining the air chamber it was found to be entirely filled with water, and it had probably been in that condition for a considerable length of time. Water under pressure absorbs air with great facility. An air chamber should be provided with an air pump

which may be readily connected to some convenient source of power, and with a gauge glass to show the water level. When so arranged, and if of ample size, it affords considerable safety against pressure developed when load goes off suddenly; but it is of no practical use as an aid to the governor in maintaining constant speed.

Aside from designing the water column along the lines already suggested, so that the water may gain its working velocity in the least possible time and also so that it may add to or take from the water-wheel the least amount of the kinetic energy of the water, the next most important thing is the design of the water-wheel gates and the method of connecting them to the governor.

As has already been pointed out, the gates are of necessity large and heavy, and yet they must be moved with great promptness and precision. The writer has had occasion to investigate with more or less accuracy the number of foot pounds necessary to open and close the gates of several hundred water-wheels, and the surprisingly large variation in the amount of energy required, leads him inevitably to the conclusion that this matter has not received in many cases the careful engineering treatment which it deserves.

Water-wheels are of many designs and sizes, and work under many different conditions of head, but there would seem to be no adequate reason why the gate of one water-wheel developing a certain amount of power under a given head should require only 1,000 foot pounds to completely open it, and the gate of another water-wheel of different make, developing the same amount of power under the same head, should require 60,000 foot pounds. Yet such has been found to be the case. The above example, taken from actual practice, is by no means unusual; and scores of such cases could be cited showing relatively absurd figures.

Some builders prefer to use cylinder gates on their wheels; others prefer wicket gates; while still others adhere to register gates. It is not the intention of this paper to enter into a critical comparison of the merits of these various types of gate, and, in fact, from the standpoint of speed regulation, no such comparison is necessary for the good and sufficient reason that there are wheels on the market of all three of the above kinds which show little to be desired in the ease with which the gates may be moved. It is also true that there are makes of wheels of all

three kinds which cannot be governed accurately under variable loads, simply for the reason that their gates cannot be moved quickly enough.

It is often necessary to start a gate from a rest and completely open or close it in two or three seconds, or give it a proportionately smaller motion in a proportionately shorter space of time. Or, what is still more severe, it is often necessary that while a gate is opening or closing, its motion be instantly stopped and reversed.

If one will watch a thoroughly first-class governor handling the gates of a water-wheel which is driving an electric generator operating on a variable load, one is convinced of the fact that the governor has to develop considerable amounts of energy in surprisingly short spaces of time, and that the rigging connecting the governor and the gates is subjected necessarily to considerable strain, from which it follows that the easier the gates move the less chance there is of stripping gears and twisting off shafts; to say nothing of relieving the governor itself of unnecessary strain.

All gears between governor and gate,—except immersed racks and pinions,—should be cut, of first class workmanship and not too large for the work required of them. The latter precaution is necessary to prevent the  $MV^2$  energy in the gears themselves destroying the rigging when the direction of motion is suddenly reversed. Shafts should be of just sufficient size to give an ample factor of safety, and prevent torsional difficulties, for it is absolutely necessary that the smallest amount of motion of the governor shall be transmitted accurately to the water-wheel gate. Lost motion in gears, and twisting of shafts are fatal to good regulation. Hand-wheels should be so arranged that they may entirely thrown out of connection with the rigging while the governor is in action, or they may be unkeyed in some simple manner.

Counterbalancing a gate is not the equivalent of having it in water balance. All vertical cylinder gates are necessarily out of balance to an amount equal to their immersed weight, but that is usually so small that it is not necessary to counteract it with a counterweight.

Some designs of gate show a violent tendency to close or stay closed. It is the custom to counterbalance such gates, and this practice leads to endless trouble an account of the kinetic energy

in the counterweight. It being often necessary to reverse the motion of the counterweight suddenly, the kinetic energy expended at the moment of reversal, is often sufficient to wreck the rigging. If counterweights must be used, it should be remembered that their kinetic energy is proportional to their weight, and also proportional to the square of their velocities; from which it follows that a heavy, slow-moving weight does less damage than a light, rapid-moving one.

Some general statements may be made in regard to the design of water-wheel gates adapted to plants in which it is desirable to obtain good speed regulation.

It has been the custom of late to cast onto cylinder gates, fingers reaching out between the guides. These innocent looking devices, which are supposed to guide the water into the wheel properly, and hence raise its efficiency, are a source of no end of trouble when it comes to moving the gate quickly enough to produce good speed regulation. The direction of motion of the water as it enters the wheel is always such that it presses these fingers downward with tremendous force, giving the gate a strong tendency to close. By removing these fingers, the amount of energy necessary to open the gates can always be reduced by, at least, one-half, and often times more than that. There are scores of water-wheels on record which were so much out of balance, due to the fingers on the gates, that it was found impracticable to govern them satisfactorily on account of gears stripping and shafts twisting off. In the writer's experience, it has always been found practicable to govern these wheels by removing the fingers.

Now, as to the question of efficiency. The writer has often had to meet the argument of the few per cent. of efficiency supposed to be lost by removing these fingers, and to answer this question, tests have been made which show that there is no material gain in the efficiency of a water-wheel set under ordinary working conditions, by attaching fingers to the gate.

Two vertical cylinder-gate wheels of the same size and make, were set in open flumes side by side. The head was precisely the same in both cases. Both wheels drove electric generators of the same make, type and size. Both wheels were furnished by the maker with cylinder gates, precisely alike and provided with fingers. It was found impracticable to govern these wheels properly, on account of the gates working so hard and being so

much out of balance. The fingers were removed from the gate of one wheel, and it was at once found that the wheel governed very satisfactorily under a very variable load. Then a test was made of the efficiency of the two wheels, one with, and one without fingers on the gates. Wires were brought up from the gates, carried over pulleys, kept taut by small weights, and they terminated in pointers reading on the same scale. A constant electrical load was switched onto one generator, and the position of the pointer indicating gate position was noted. Then the load was switched onto the other generator (the speed being kept the same in both cases) and it was noted that the pointer of the second unit stood at the same point at which the pointer of the first unit had previously stood. This experiment was repeatedly tried at a number of different loads, from slightly above friction load, to nearly the full capacity of the wheels. So far as could be observed, the efficiency of the wheel without fingers on the gate, was as good as that of the wheel with the fingers. The particular test above described, was made by Mr. J. H. Wilson, in the plant of the Berlin Mills Co., Berlin Mills, N. H.

The writer is aware that this test is not the equivalent of a Holyoke test, but it is certainly of great interest to the practical engineer who is harassed by the thought that in avoiding the Scylla of bad efficiency, he will surely be wrecked on the Charybdis of an ungovernable gate.

There are a number of other details of cylinder-gate construction which time and space will not permit us to touch upon here, but which should be considered by the thoughtful engineer before making a selection. The thing to be borne in mind is that the cylinder and its connections should be of such design that they may be easily moved, and will not bind and run hard in any portion of their travel.

Wicket gates also have their peculiarities. Some makers hang them in such a manner that they are practically in water balance in any position, and may be readily opened and closed with a small expenditure of energy. Such gates leave little to be desired, and wheels fitted with gates so designed may be governed with the greatest degree of exactness and without fear of injury to the rigging or governor. The writer has observed, however, that some wicket gates which move very easily have so much lost motion that in certain portions they tend to flop (no other



word conveys the idea) first in one direction and then in the other, causing a pulsating speed which is very annoying and apparently inexplicable until one has investigated the cause. The danger of lost motion is greater with wicket than with cylinder gates, but with proper construction it is found in practice that lost motion may be entirely eliminated from wicket gates.

In some wicket-gate wheels the wickets are hinged at one end and attached by the other end by tangential arms to a banjo, which in turn is geared to the shaft going to the governor. Such gates are entirely out of water balance when partly closed, and the more they are closed the more they are out of balance. Wheels with gates of this description are very difficult to govern. Frequently the strength of the wickets and radial arms is not sufficient to withstand the water pressure, even if sufficient energy can be supplied to them. In recent practice a wheel of this description was found to require some 40,000 foot pounds to open it. Another wicket-gate wheel of different make but the same rated H. P. was found to require only 5,000 foot pounds to open it. As another recent instance, it was found that a pair of wicket-gate wheels of the kind described above required 19,000 foot pounds to open them: another pair of different make but the same rated H. P. required but 2,500 foot pounds to open them. The wheels compared above were working under the same head.

The way a maker proposes to rig his gate is a good indication of the amount of energy he thinks it will take to move it. If he thinks it is necessary to use worm gears or multiplying gears giving a large number of turns to the hand-wheel it is safe to conclude that in his opinion,—and he certainly ought to know,—the gate will move hard or be much out of balance. Such wheels it is safe to leave alone if accurate speed regulation under variable load is the end in view.

All practical engineering is a compromise between the desire of the engineer on the one hand to produce a perfect piece of engineering, and the unwillingness of the stockholders on the other hand to invest money which will not bring direct returns in the shape of dividends, or, to state the matter more conservatively, there is always a point in each plant beyond which investment must not go, and this point is different for each plant, being fixed by the economic conditions which surround the particular enterprise.

For the above reasons it is impossible to lay down hard and

fast rules for the development of water powers. Assuming that the value of all engineering is measured by the dividends earned, what would be good engineering in one case is bad engineering in another. Yet, it is equally true that in an electric plant driven by water power the worst possible place to economize is in the channels and conduits which bring the water to and away from the water-wheels, and in the water-wheels themselves and their governors. Dollars saved here are apt to be expensive economy.

The infinite variety in which natural water powers present themselves makes this a difficult branch of engineering, and much is yet to be learned about it. Yet, it is safe to say that enough is now known about the subject to permit almost any naturally good water power to be so developed and utilized that the plant driven by it may be as readily controlled and its speed maintained as constant as though the driven load were carried by first-class steam engines. It should, however, be remembered that no matter how well the plant is designed, good speed regulation cannot be obtained unless the water-wheel governors are of correct design and well built. The value of a governor is measured by two things—the promptness and ease with which it will move the water-wheel gates to the correct position and stop them when they get there, and its ability to compensate by adjustment of the gate for the kinetic energy in the moving water column. One might add sensitiveness as a mark of a good governor, but nearly all modern governors are very sensitive, though most of them sadly lack the other two qualifications named above. The best made governors on the market will begin to move the water-wheel gates before any tachometer on the market will show a change in speed, yet they would not govern if they did not know when to stop as well as when to start.

I have been requested by a number of gentlemen to say something about fly-wheels. We may approach this subject in the following manner:—

When we wish to find out how much energy is stored in a revolving fly-wheel we begin by finding its moment of inertia, which is its weight multiplied by the square of its radius of gyration.

Let  $J$  = radius of gyration in feet.

$W$  = weight in pounds.

$I$  = moment of inertia.

$$I = W J^2 \quad (19)$$

The energy in foot pounds stored in the revolving wheel is as follows:

Let

$\mathfrak{E}$  = energy stored in the wheel.

$$a = \text{angular velocity in radians per second} = \frac{2 n \pi}{60} \quad (20)$$

where

$n$  = revolutions per minute

and

$$\pi = 3.14159$$

Then

$$\mathfrak{E} = \frac{I a^2}{2} \quad (21)$$

Substituting the value of  $a$  we get

$$\mathfrak{E} = \frac{I \left( \frac{2 n \pi}{60} \right)^2}{2} \quad (22)$$

Evolving which we get

$$\mathfrak{E} = \frac{I n^2 \pi^2}{1800} \quad (23)$$

Which is the form in which the formula is ordinarily used.

It may be simplified for

$$\frac{\pi^2}{1800} = .00551 \text{ is a constant.}$$

Substituting this we get (24)

$$\mathfrak{E} = I n^2 \times .00551$$

But you will note that this expression may be conveniently divided into two parts, as follows:

$$\mathfrak{E} = n^2 \times (I \times .00551) \quad (25)$$

Which is equivalent to saying that every fly-wheel possesses a certain quantity, which, multiplied by the square of its revolutions per minute, equals the foot pounds of energy stored in it. This quantity is its  $(I \times .00551)$  which we may symbolize by  $\mathfrak{N}$  and we may write

$$\mathfrak{E} = n^2 \mathfrak{N} \quad (26)$$

Or, substituting our value of  $I$  we may write

$$\mathfrak{E} = n^2 (W \times J^2 \times .00551) \quad (27)$$

It is evident that this value of  $\mathfrak{N}$  which is the energy stored in the wheel when making one revolution per minute when once found for any particular fly-wheel may be used at once to calculate its energy at any speed, simply by multiplying it by the square of its revolutions per minute.

This value of  $\mathfrak{N}$  for the rim of any fly-wheel may be found as follows:

Let

$w$  = weight in pounds of one cubic foot of the metal of which it is made.

$d$  = outside diameter of rim in feet.

$d_1$  = inside diameter of rim in feet.

$l$  = face of rim in feet.

Then

$$\mathfrak{N} = \frac{w l (d^4 - d_1^4)}{59,814} \quad (28)$$

But a close enough approximation to the  $\mathfrak{N}$  of a cast-iron fly-wheel of usual shape with light arms may be found as follows:

Let

$W$  = weight of wheel in pounds

$d$  = mean diameter of rim.

Then

$$\mathfrak{N} = \frac{W d^2}{23,000} \quad (29)$$

Now the question is how much of a fly-wheel do we require in any particular case. Let us return to wheel No. 1 in Fig. 4.

We remember that when the gate of this wheel was suddenly opened wide it was .7 second before the water was doing its full amount of work on the runner. We must also remember that the curve 0 - 1 (see Fig. 7) with which the water got up to full power was a parabola. The area outside the parabolic line was the work which the water did do in this .7 second, and the area inside this parabolic line was the work which the water failed to do in the same time. From the law of areas of parabolas it follows that the area inside this curve (which is a half parabola) is two-thirds of the area of the rectangle enclosing the curve. Or we may say more simply that while the wheel was getting up to speed it performed one-third of the work which it would have done in the same time had it been working at full gate and full speed.

Let us begin to apply this to the design of a suitable fly-wheel. Assume, for simplicity of calculation, that the water wheel is about 48" in diameter and at full gate develops 100 H.P. and runs at 75 R.P.M. Let us also assume that it must not, upon the whole load being instantly thrown on or off, run more than 4 per cent. below or above normal. Its minimum speed must be then

$$75 - \frac{75 \times 4}{100} = 72 \text{ R.P.M.}$$

and its maximum speed must be

$$75 + \frac{75 \times 4}{100} = 78 \text{ R.P.M.}$$

We must also remember that it was found that we could not completely open the gates in less than two seconds. Therefore, supposing that the rate of opening the gate was uniform, the average gate opening during the two seconds was only one half, and if the wheel during every instant of time had been developing the full power due to the instantaneous value of gate opening it would have developed only one-half as many foot pounds as though it had been at full gate for two seconds. But we found that the power lagged .7 second behind the gate opening, during which time it developed only one-third of the power due to the gate opening; hence, for two seconds the wheel developed  $\frac{1}{3}$  of  $\frac{1}{2}$  the power it would have developed during the same time at full

gate, and for .7 second more it developed  $\frac{1}{3}$  of full power. Reducing this to foot pounds we have

$$\frac{100 \times 550 \times 2}{6} = 18333 \text{ foot pounds.}$$

$$\frac{100 \times 550 \times .7}{3} = \underline{12833} \text{ foot pounds.}$$

Adding these we get 31166 foot pounds, which is the total energy developed by the water-wheel in 2.7 seconds.

If working at full gate and maximum flume velocity for that length of time it would have developed

$$100 \times 550 \times 2.7 = 110000 \text{ foot pounds}$$

$$\text{Subtracting from this} \quad \underline{31166} \quad " \quad "$$

We get 78834 foot pounds, which is the amount of energy which must be developed by the fly-wheel before its speed is reduced to 72 R.P.M.

Let us assume that the fly-wheel makes the same number of revolutions as the water-wheel.

Its energy at 78 R.P.M. is

$$\mathfrak{N} \times 75^2 = \mathfrak{N} \times 5625$$

Its energy at 75 R.P.M. is

$$\mathfrak{N} \times 72^2 = \mathfrak{N} \times \underline{5184}$$

Subtracting one from the other we get 441

The value of  $\mathfrak{N}$  is therefore

$$\mathfrak{N} = \frac{78834}{441} = 178$$

From the above value of  $\mathfrak{N}$  should be deducted the  $\mathfrak{N}$  of the water-wheel itself and the other rotating parts such as pulleys and armatures. For simplicity of calculation I shall not make this deduction in this case, and we will proceed to design a fly-wheel of suitable proportions, which shall have an  $\mathfrak{N}$  value numerically equal to 178.

As it is to be of cast-iron we will limit its peripheral speed to 65 feet per second.

Let  $d$  = its outside diameter in feet.

$p$  = its peripheral speed in feet per second.

$R$  = revolutions per minute.

Then

$$d = \frac{p \times 60}{R \pi}$$

Applying numerical values we get

$$d = \frac{65 \times 60}{78 \times 3.14} = 15.5 +$$

Assume  $d_1$  or the diameter inside the rim = 14.5 feet

Transpose formula No. 28 so as to get  $\ell$  or the face of the wheel in feet.

$$\ell = \frac{\pi \times 59814}{w \times (d^4 - d_1^4)} \quad (30)$$

Applying numerical values we get

$$\ell = \frac{178 \times 59814}{450 \times (15.5^4 - 14.5^4)} = 1.6 \text{ feet} = 1 \text{ ft. } 7 \text{ in. nearly.}$$

Our fly-wheel rim is, therefore, 15 feet 6 inches outside diameter, 6 inches thick, and 1 foot 7 inches wide on the face, and would weigh 16,992 lbs.

This strikes one as a very large fly-wheel for a 100 H. P. unit, but it must be remembered that it is intended to perform very severe duty. Moreover, no allowance has been made for the kinetic energy in the fly-wheel arms, nor in the water-wheel itself and other rotating parts. All of these corrections should be made and the proper deduction made from the fly-wheel above designed.

Another correction should also be made which would still further reduce the size of the fly-wheel.

It was assumed that the water-wheel was working at normal speed and friction load when the whole load was thrown on. Friction load is a part of whole load, and hence when we say we throw on whole load, we really mean that we are throwing on something less than 100 H. P. Also, at friction load the water

in the flume had some velocity, and hence we did not have to start the water from a condition of rest, but from a condition of slow velocity.

To make all these corrections involves a considerable knowledge of hydraulics and mechanics. To treat this subject in a complete manner, would involve a good many figures, and would extend this paper far beyond proper limits.

It may be noted here that if it is found desirable to change the value of  $\mathfrak{N}$  of a fly-wheel after it is designed, it is not necessary to re-design the wheel. The dimensions of fly-wheels are as the fifth roots of their  $\mathfrak{N}$ 's. We have found a fly-wheel whose  $\mathfrak{N} = 178$ . If we now wish to reduce its  $\mathfrak{N}$  to 150, we write

$$\sqrt[5]{178} : \sqrt[5]{150} = 15.5 : \text{diameter}$$

From which we get

$$\text{diameter} = \frac{\sqrt[5]{150} \times 15.5}{\sqrt[5]{178}} = 15.0 \text{ feet.}$$

or formularizing it we get

$$D_1 = \frac{\sqrt[5]{\mathfrak{N}_1} \times D}{\sqrt[5]{\mathfrak{N}}}$$

Where

$D$  = diameter of wheel having given  $\mathfrak{N}$

$D_1$  = diameter of required wheel

$\mathfrak{N}$  = given value of  $\mathfrak{N}$

$\mathfrak{N}_1$  = required value of  $\mathfrak{N}$ .

All of the linear dimensions should be treated in the same way. For example: if we have a design of a fly-wheel drawn to a scale of one inch to the foot, and in building the wheel we read the drawing as though it were one-half inch to the foot, then the  $\mathfrak{N}$  of the fly-wheel will be  $2^5 = 32$  times as large as it would have been if the wheel had been built according to the scale of one inch to the foot.



Where we have a fly-wheel of a given  $\mathfrak{N}$  and we know how many foot pounds it will be required to give up or absorb, as the case may be, we may find the resulting speed by the following formula:

$$r = \sqrt{\frac{\mathfrak{S} - \mathfrak{S}_1}{\mathfrak{N}}} \quad (32)$$

where  $r$  = the final revolutions per minute.

$\mathfrak{S}$  = energy in foot pounds stored in wheel at normal speed.

$\mathfrak{S}_1$  = energy in foot pounds required of the wheel.

$\mathfrak{N}$  = energy in wheel when making one revolution per minute.

The above formula may be more conveniently as follows:

$$r = \sqrt{\frac{(\mathfrak{N} \times R^2) - \mathfrak{S}_1}{\mathfrak{N}}} \quad (33)$$

where  $R$  = normal revolutions per minute. Applying to the wheel we have been discussing we have

$$r = \sqrt{\frac{(178. \times 75^2) - 78,834}{178.}} = 72$$

which is the minimum revolutions per minute which we first agreed upon.

We have seen that to make even an approximate design of fly-wheel we have required considerable data to work from, and have been obliged to do quite a little figuring, and yet the water-wheel in question was set in the simplest possible manner. Had it been set in a closed flume like wheel No. 2, (Fig. 4,) the problem would have been greatly complicated.

In view of these facts, it becomes quite amusing to note the alleged accuracy with which statements are often made in regard to the exact amount of fly-wheel which is required to give stated degrees of speed regulation upon 10%, 25%, 50%, etc., of the load being instantly thrown off or on, when it is perfectly evident that only part of the data is available which would enable only approximate figures to be made.

The one concluding crumb of comfort which the writer is able to offer, is found in the fact that in a very large practice, he

has never found it necessary with a water-wheel set in an open flume, to install a fly-wheel in order to obtain a perfectly satisfactory speed regulation under any operating conditions of an electric plant. The various rotating parts of the plant, such as water-wheels, armatures, pulleys, etc., have sufficient moment of inertia and angular velocity to enable a first-class governor to hold the speed within very satisfactory limits under any sudden load changes which occur in the actual operation of the plant.

If the design of the hydraulic part of the plant is bad, it is wiser to try and improve it, rather than lean largely on fly-wheel effect, which is a weak prop at the best.

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#### DISCUSSION.

MR. CHARLES F. HOPEWELL:—I would like to ask if the length of the draft tubes makes any difference.

MR. GARRATT:—As a matter of practical experience I have found the more of the head you have above the wheel and the less below it the better the regulation you can obtain, for the practical reason that when wheel builders don't make things tight, and when the pressure is from the inward outward it simply means that a little water leaks out, but when the pressure is the other way it means that the air leaks in. The more air you can keep out of your pipes the better regulation you will invariably get. There is no danger of air getting in above the wheel, but very great danger of it getting in below the wheel. So that it is well to put as much of the head above as you can.

PROF. W. S. ALDRICH:—Almost all of the cases given here relate to the reaction or pressure type of wheel. Of course, that is the most difficult to govern. The ordinary impulse water wheel is most easily controlled. The paper evidently proposes to consider only the type of wheels of the reaction or pressure kind. In the western states, wheels are being operated under very high heads which have brought out characteristic methods of speed regulation. Again, methods of regulation such as by throttling the discharge, have been adopted for the reaction or pressure wheels that are suitable only to that type and to be noted particularly in the Niagara plant. But the references in the paper relate entirely to methods of regulation affecting the flow.

The views shown on the screen were of a relay type of governor, a type not proposed for discussion in the paper, but which is coming into more general use for flow regulation of low and medium heads on pressure wheels. Regulating water-wheels by controlling the discharge is, of course, more particularly adapted to installations of the Niagara class; but there seems no reason why it should not be successfully employed in