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THEORY AND TEST OF AN OVERSHOT WATER WHEEL

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RESEARCHES IN HYDRAULICS
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THE DESIGN
OF THE
HOMEMADE OVERSHOT WATERWHEEL

PROGRESS REPORT NO. 1

BY

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SCHOOL OF
AGRICULTURE AND FORESTRY
RESEARCH EXTENSION
RESIDENT TEACHING

DEPARTMENT OF AGRONOMY
DIVISION OF
FARM CROPS

May 4, 1938.

Professor D.S.Weaver
Ricks Hall

Dear Professor Weaver:

Enclosed is a copy of a progress report on the research work done to date on the overshot waterwheel. It consists of the theory of the overshot wheel, and the design and construction of the experimental wheel. This copy may be filed for the department.

I would be pleased to have you or some member of the extension force study this report with a view towards giving suggestions or any help in reaching the final objectives of this research. Mr. Broaddus indicated that he was very much interested in this problem.

Broaddus

This research as planned will take several years but I wish to settle for good this problem of waterwheel design and get the results in a simple form, usable by the extension engineer.

Yours very truly,

G Wallace Giles

G. Wallace Giles
Assistant Professor of Agricultural Engineering

GWG-h

DEPARTMENT OF AGRICULTURAL ENGINEERING

NORTH CAROLINA STATE COLLEGE OF AGRICULTURAL ENGINEERING

PROGRESS REPORT NO. I
THE DESIGN OF THE HOMEMADE OVERSHOT WATER WHEEL

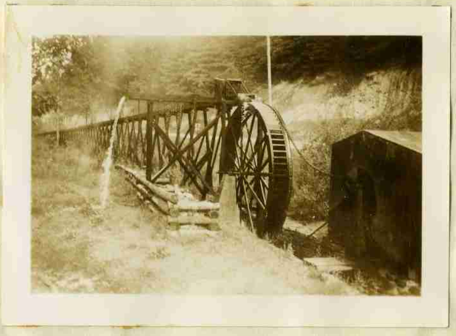
BY

G. WALLACE GILES
ASSISTANT PROFESSOR OF AGRICULTURAL ENGINEERING

OBJECTIVE NO. I

" TO DETERMINE THE CORRECT AND MOST PRACTICAL DESIGN PROCEDURE FOR A HOMEMADE OVERSHOT WATER WHEEL " .

January 30, 1938.



Typical Homemade Overshot Water Wheels in North Carolina.

F O R E W O R D

This research on " The Design of The Homemade Overshot Waterwheel"was made possible by the aide of the State College Research Fund.

SUMMARY OF THE REPORT

Introduction

1. There is still need for the development of water power on the farm, particularly on the farms which will always be isolated from the power lines.
2. The overshot water wheel is the most efficient type of wheel. It is also the easiest to construct and to install by the farmer.
3. The extension agricultural engineer does not have any simple, reliable data to aid him in helping the farmer build and install an overshot water wheel.

Review of Literature.

1. There is no recent work on overshot water wheels. Most of the experimental work was done prior to 1840 by foreign experimenters. The apparatus used in these experiments was very crude. Most of the work consisted of efficiency tests on commercial sized wheels, and very little was done to assist in the design of homemade wheels.
2. The most recent work was performed by Carl Weidner in 1913 at the University of Wisconsin. Efficiency tests were performed on a 10 foot commercial wheel of metal construction.

Objectives

The objectives of this research are to:

1. Determine the correct and most practical procedure for a homemade overshot waterwheel.
2. Put the proper design procedure into table or some simple form whereby the extension agricultural engineer may quickly and efficiently supply the farmer with correct dimensions for his particular conditions.
3. Work out simple construction features that may be applied to any homemade wheel and which will keep the efficiency as high as possible.
4. Design simple, efficient means of transmitting the power of the wheel to the desired machines.

Plan of Procedure for Objective No. 1 .

Step No. 1- The theory of the overshot water wheel.

Step No. 2- The design of the experimental water wheel according to the theory.

Step No. 3- The construction of the experimental water wheel and set-up of the laboratory apparatus.

Step No. 4- Efficiency tests.

Step No. 1 for Objective No. 1.

" Theory of the overshot water wheel. "

1. The theory of the overshot water wheels as worked out by Prof. Bach, a German engineer, is presented. It is the best theory on the overshot water wheel. The theory is presented in a manner that is thought to be easily understood by the average man.

2. The entrance water should have a velocity greater than the peripheral velocity of the wheel. The following equation may hold:

$$\text{Entrance velocity} = (C_h = 4.54\sqrt{V}$$

3. Knowing the entrance velocity, the amount of head required to produce the velocity and then the diameter of the wheel may be determined.
4. The water leaving the entrance spout will take a parabolic path.
5. To prevent a serious loss due to the impact of the back of the bucket with the entrance stream, the bucket should be shaped according to the relative path (path of the water with respect to the wheel).
6. To prevent a greater loss due to the early exit of the water the buckets should be inclined more than the slope of the relative path.
7. The water should enter the bucket in such a manner that the bucket will be filled and impact will occur as high in the wheel as possible.
8. The buckets should be relatively shallow in order that the center of gravity of the water will be as far from the center of the wheel as possible.
9. For maximum efficiency the buckets should be 1/3 to 1/2 full. Too much water will be lost due to early exit and it is thought best in most cases to make the wheel wider to take care of the quantity of water.

Step No. 2 for Objective No. 1

"Design of a laboratory experimental wheel according to the theory".

Data:

Q = quantity of water = 310 gal/min = .7 cu. ft/sec.
R = number of rev/min = 15.
D = diameter = 6 feet
Na = theoretical power of the water = .55 H. P.

2. Peripheral velocity of the wheel = 4.71 feet/sec.
Entrance velocity of the water = 9.9 feet/sec.

3. Location of the center line of the streams below the surface of the water to produce an entrance velocity of 9.9 feet/sec = 1.70 feet.

4. Radial depth of the buckets = 4 1/2"
Width of buckets = 12"

5. Horizontal distance between entrance spout and the center of the wheel = 9 inches.

6. Depth of the entrance stream = 1.02 inches.

7. Width of bucket opening measured on outer circumference of the wheel = .524 feet.

8. Number of buckets = 36

9. The first homemade bucket will be made of two strait pieces, one a radial piece 1 1/2" wide fastened to the bottom or soling. The other piece is 8 3/4" wide and inclined back from the radial piece to the outer circumference.

10. The computed theoretical efficiency for this first wheel with the homemade buckets is 72 per cent.

Step No. 3 for Objective No. 1

" Construction of the experimental wheel and the arrangement of the laboratory apparatus".

1. Construction details of the buckets and the 6 foot water wheel is shown in Fig. 7.

(a) the wheel is built on the rear axle assembly of an automobile. The axle housing is cut in two and mounted on concrete pedestals with wheels facing each other.

(b) The auto wheels are removed from the brake drum and water wheel spokes are bolted in their place.

(c) The power is taken off from the propellor shaft after going thru the differentntial gearing which increases the speed 4 times.

2. Fig. 8 shows a schematic drawing of the laboratory arrangement.

(a) A 3" centrifugal pump circulates the water from a lower tank to an upper tank where it enters the wheel enptied in a metal flume and returned to the lower tank.

(b) The water enters the lower tank from the flume thru a rectangular weir where the quantity of water is measured.

(c) An adjustable gate in the upper tank controls the depth and quantity of the entrance water.

(d) A valve on the centrifugal pump keeps the head of water on the wheel constant.

(e) The output of the wheel will be measured by an 1 K.W. Electric dynamometer driven by V-belt from the propellor shaft on the differential. The speed of the generator on the dynamometer will be approximately 900 R.P.M.(rated R.P.M. of the generator is 1200 R.P.M.)

INTRODUCTION

In the State of North Carolina there are a large numbers of streams flowing the year around. Many of these streams are of such nature that they may be economically harnessed to provide a source of power for the farm. This power may be used for generating electricity or operating a number of useful machines.

The simpliest and cheapest means of converting this water power into useful energy is by the use of overshot water wheel. It is the one water wheel that may be constructed by the farmer, himself, with materials and tools found on his own place or in a nearby village. If properly constructed it is the most efficient type of water wheel. The efficiency is not affected as much by poor design or construction as other types of wheels, and it requires practically no attention or upkeep.

Many farmers have constructed their own wheels in the past and many still continue to do so - crude perhaps and not very efficient, but never-the-less they operate satisfactorily. In the successful cases sufficient water is available to take care of this inefficiency. Many farmers desire to make their own water wheel but lack knowledge of proper dimensions and construction features. This is indicated by the requests received by the Department of Agricultural Engineering. Then too there is the case of the farmer who has just sufficient water to give him the amount of power needed. He must build an efficient wheel or failure will result. It is important that good construction be used. To do this accurate data on dimensions, shape of buckets, position and manner of entrance water is necessary. The farmer should expect to receive help from the extension agricultural engineer. No accurate information or data is available to help the farmer.

It is true that electrical energy is being made available to a large number of farms. The number of farms using electrical energy in the future is destined to increase, but there will be some farms isolated from the power line. Many consider the overshot water wheel as out of date and a thing of the past. However, we are still faced with the fact that flowing water on a farm may be converted into practically free power(electrical or otherwise). This interests the farmer and will always do so unless the farm income is greatly raised. It would be folly indeed for a farmer, particularly one who is mechanically inclined, to disregard this free power available on his own farm. This power will not be cut off in case his bills can not be paid. An overshot wheel can supply this power in the most efficient manner.

REVIEW OF LITERATURE

1. Weidner, Carl R.- University of Wisconsin, 1913.

Efficiency tests were performed on a 10 foot metal commercial type wheel. The following are the conclusions.

(1) The maximum efficiency obtained was 89 per cent at the wheel shaft and 86 per cent at the jack shaft. The transmission loss thru gears was then 3 per cent at this maximum efficiency. For operating high speed machinery a 3 per cent to 10 per cent loss may occur thru the gearing or belting.

(2) The efficiency of the wheel, other conditions remaining constant, increased with the decrease in the entrance velocity of the water. The wheel was not tested with very low entrance velocity. The statement is limited to the fact that the entrance velocity must be greater than the peripheral velocity of the wheel. For maximum efficiency the ratio of the peripheral velocity to entrance velocity is .9 .

(3) Variation in the discharge of the water into the buckets does not affect the efficiency if the buckets are no more than one-half filled.

(4) sumbergence of the wheel in the tail water caused a serious decrease in efficiency. A 3 inch submergence caused a 6 per cent loss which rapidly increased with increase in submergence.

(5) For maximum efficiency, the point at which the water hits the bucket should lie as high on the wheel as possible. This point is regulated by the horizontal distance of the entrance spont or orifice from the cneter of the wheel. Professor Bach's formula for determining this distance is reliable. This distance

must be adjusted for each installation, otherwise a serious loss of energy occurs at the entrance. This may be adjusted by observation. If the entrance is too far away some of the water will fall down at the rear of the wheel and if the entrance is too close to the center of the wheel some of the water will shoot over the first bucket and fall in the second or third bucket from the crown.

2. Smeaton, John, English Engineer, 1752 & 1753.

Experiments were performed on model wheels, 2 feet in diameter and results verified by practical installations. It must be remembered the equipment and methods were crude in the early days. The following are the conclusions:

(1) The efficiency varied between 52 and 76 per cent.

(2) The highest efficiencies were obtained when the head on the wheel was small and thus the entrance velocity is low. However it is desirable to have the entrance velocity somewhat greater than the peripheral velocity of the wheel. The peripheral velocity for maximum efficiency is 3 feet per second and for larger wheels this may vary considerably without affecting the efficiency.

3. Franklin Institute, 1829.

A committee was appointed by the Franklin Institute to ascertain by experiment the value of water as a moving power. Experiments were performed on 4 wheels, 20 feet, 15 feet, 10 feet and 6 feet. The width of the buckets was 16 inches. The wheels were operated as overshot breast and undershot. The following are the conslusions on the overshot wheels.

(1) The 20 foot wheel gave efficiencies of 82.3 to 84.5 per cent with heads on the wheel varying from 2.75 to .50 feet. The lower heads gave better efficiencies.

(2) The ratio of the peripheral velocity to the entrance velocity should be .55 for maximum efficiency.

(3) The decrease in efficiency from the 20 foot wheel to the 6 foot wheel was 3 per cent, other conditions remaining the same.

(4) 20 and 40 elbow buckets were compared. The average efficiency was the same.

4. Arthur, Morin, 1829 to 1835.

A number of experiments were performed on various commercial wheels. The following are the conslusions on four overshot water wheels with diameters ranging from 7.5 to 30 feet.

(1) The head on the orifice must be proportioned to the diameter of the wheel or to the total head, and the peripheral velocity can be as high as 6.25 feet per second for the smallest wheel. and 8 feet per second for the largest, without materially decreasing the efficiency.

(2) The ratio of the peripheral velocity of the wheel to the velocity of the water entering the wheel, may vary within wide limits. For large wheels this ratio may be taken between 0.30 and 0.80, but for small wheels it is better to limit this variation between 0.40 and 0.60. This fact that the speed of the wheel may be varied without materially decreasing the efficiency is one of the advantages of this type of wheel, and renders them useful for factories, where the speed of the machinery has frequently to undergo considerable variation.

(3) The efficiency of this type of wheel varies between 65 and 70 per cent.

OBJECTIVES

The objectives of this research are to:

1. Determine the correct and most practical design procedure for a homemade overshot waterwheel.
2. Put the proper design procedure into table or some simple form whereby the extension agricultural engineer may quickly and efficiently supply the farmer with correct dimensions for his particular conditions.
3. Work out simple construction features that may be applied to any homemade wheel and which will keep the efficiency as high as possible.
4. Design simple, efficient means of transmitting the power of the wheel to the desired machines.

Plan of Procedure for Objective No. 1.

<u>To Determine the Correct and Most Practical Design Procedure for a Homemade Overshot Water Wheel.</u>

Step No. 1. The theory of the overshot water wheel.

The theory as worked out by Professor Bach, a German engineer, is presented in a form that is thought to be easily understood. Additional explanation is added for clearness. This theory is taken from Bulletin No. 529 by Carl R. Weidner of the University of Wisconsin, entitled, " Theory and Tests of an Overshot Water Wheel " It must be remembered that this relates to German practice.

Step No. 2. Design of the experimental water wheel according to the theory. A 6 foot wheel will be designed, for the laboratory, on which experinemtal work and tests will be conducted.

Step No. 3. Construction of the experimental wheels and the arrangement of the laboratory apparatus.

In most cases it will not be possible to have home-made buckets shaped according to the theoretical curve as worked out in Step No. 2. It will probably be necessary to construct the buckets of two straight pieces. Several different types and sizes of buckets with various spacings will be built for the same wheel or a similar wheel. One set of buckets will be shaped according to the theoretical curve. The construction features will designed and many of these features may be applied to any size of wheel.

Step No. 4. Efficiency tests.

Water consumption, head on wheel, position of entrance water, velocity of wheel, and horse power output of the wheel will be measured in conducting the efficiency test. An effort will be made to substantiate the theory of the correct entrance of the water into the bucket.

This may be studied by slow motion pictures taken thru a glass window in the side of the wheel.

In conducting the tests the following points are considered.

(1) Is it reasonable that the most efficient shape of bucket, where two strait pieces are used, would be one that approaches as closely as possible the theoretical curve?

(2) How much loss is incurred by not having the bucket shaped on the curve? It will be necessary to test the wheel using buckets of correct curvature.

(3) How much loss would be incurred by building all wheels with the same bucket design regardless of size of wheel or the entrance velocity of the water? It would certainly simplify informational requirements necessary for each wheel set up. If no serious loss results one or possibly two patterns may be used with a great saving in time and money. The only change necessary would be the width and depth of the wheel.

(4) What construction features, such as shrouds, ventilators, etc., may be used to increase the efficiency of the wheel? This rightly belongs under Objective No. 3, but should be kept in mind while conducting the tests.

(5) The speed of the wheel should be kept as high as possible. The chief disadvantage of the overshot wheel is the slow speed. Generators in particular need to be driven at a high speed and a serious loss always results in the gearing.

STEP No. 1

FOR

OBJECTIVE No. 1

Theory of the Overshot Water Wheel.

This is Professor Bach's theory and design. It is taken from Bulletin 529 of the University of Wisconsin. Some of the notations have been changed for clearness and additional explanations have been added here and there particularly in those places where this author had found the study quite difficult. Professor Bach has presented his theory and proof with many complicated equations. This author had endeavored to present theory with little mathematical analysis or proof but with explanation that should make clear to the average man the reasons for suggested shape, position, etc., of the overshot wheel.

We will first discuss in a general way what happens to a stream of water as it enters the water wheel, exerts its weight during one-half of a revolution and finally leaves it. The detailed design procedure can them be studied with an example- designing the 6 foot laboratory wheel to be used for the experimental work.

There are two important events that the designing engineer is principally concerned about; (1) The entrance of the water into the wheel and (2) the exit of the water from the wheel.

We are first concerned with the velocity with which the water enters the wheel. How much of the total head should be used in giving velocity to the water ? Knowing this velocity we may arrive at an approximate diameter for the wheel.

Every wheel set-up will have a certain head of water (Fig 1). Any amount of this head of water may be converted into velocity. If the flume for the entrance of water into the wheel is high or near the top of the head, the wheel may be large in diameter and the velocity of the entrance water will be low. As the flume is lowered the entrance velocity will increase and the diameter of the wheel must be made smaller.

It must be kept in mind that the overshot wheel works due to the weight of the water being carried from the higher level to the lower level. The larger the diameter of the wheel the more power there will be generated. However, the water must have a certain velocity in order to properly fill the buckets of the wheel.

According to Bach the equation:

$$C_h = 4.54\sqrt{V}$$

where V = peripheral velocity of the wheel

and C_h = horizontal component of velocity with which the water enters the bucket

will give the proper relation of entrance velocity to peripheral velocity of a wheel.

The approximate peripheral velocity of the number of revolution per minute of the wheel should be first decided upon.

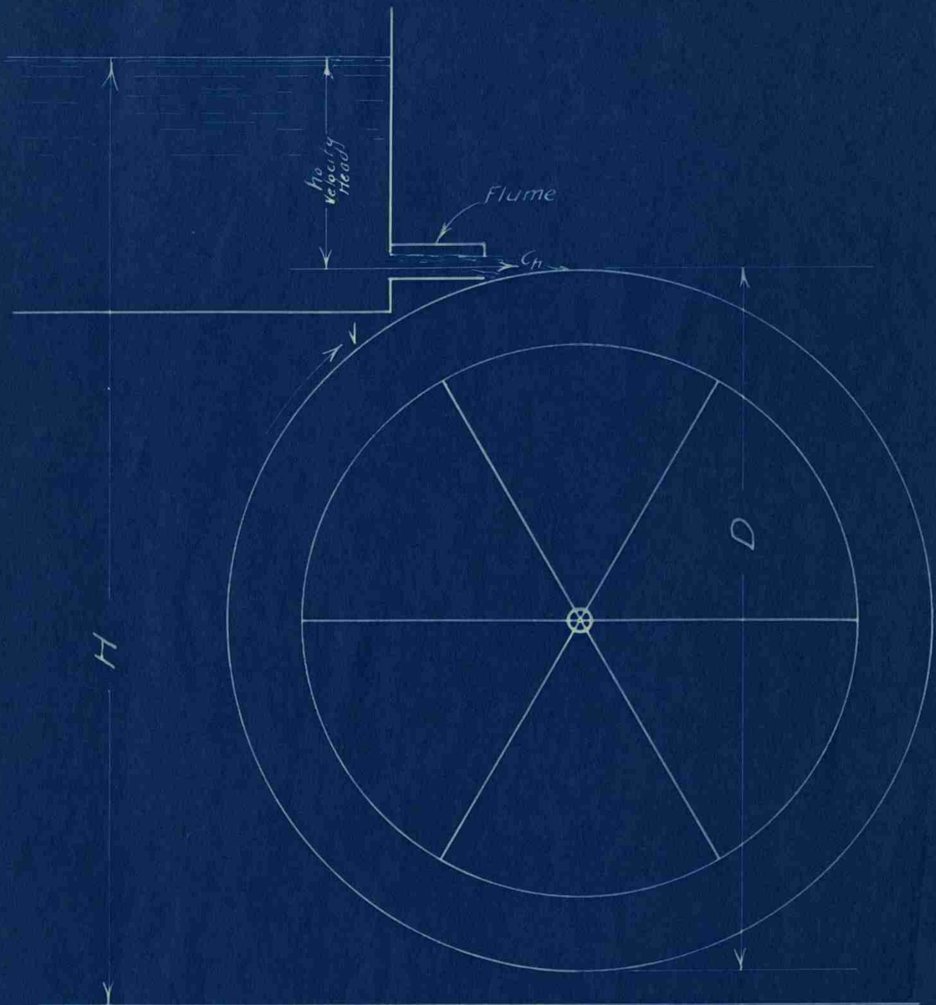


FIG. 1
Overshot Water Wheel

The approximate peripheral velocity or the number of revolution per minute of the wheel should be first decided upon.

According to Bach, decreasing V inceeases:

(1) The efficiency of the wheel up to a certain limit

(2) The width of the wheel

(3) The cost of the wheel

(4) the gear ratio and with it the weight of the gearing

(5) The cost of the gearing

(6) The loss of energy due to friction in the bearings and in the gearing.

The overshop wheel is a slow speed wheel. According to the Wisconsin Experiment the most efficient speed for a 10 foot metal, commercial, wheel was 12 to 13 R. P. M.

$$\text{Peripheral Velocity} = \frac{2 \quad \times 5 \times 12.5}{60} = 6.5 \text{ ft/sec.}$$

According to Bach the usual value of V lies between 5 and 6.5 feet per second. With small diameters the value of V would be small and with large diameters V would be large.

It seems that 12 or 13 R. P. M. would be correct for most wheels. It seems right to lose a little efficiency and make the speed higher thus reducing the gear ratio. It would thus be wise to select around 15 R. P. M.

Having decided upon the value of V the horizontal velocity of entrance water may be computed from the relation $C_h = 4.54\sqrt{V}$ According to the Wisconsin experiments the smaller the proportion of the total head adsorbed in giving velocity to the supply water, the larger the efficiency. However the experiments did not include very low entrance velocities. According to Smeaton*, who experimented with 2' models, this is true but is limited to the fact that the velocity of the water should be greater than the peripheral velocity of the wheel. The Wisconsin experiments indicated that the relation should be a bout $C_h = \frac{V}{.9}$. If we select the velocity as 6 feet per second and substituting in formula

$$C_h = 4.54 \sqrt{V}$$

we get $C_h = 11.12$ feet/sec.

Substituting in formula

$$C_h = \frac{V}{.9}$$

we get $C_h = 6.6$ feet/sec.

There is considerable difference in these values. The curves as a result of the Wiscinsin experiments are quibe broad crested indicating some variation in the ratio between entrance velocity and peripheral velocity will not greatly affect the efficiency. This author is greatly interested in what affect the entrance velocity has on the homemade wheel.

If the water is to have a horizontal velocity of C_h entering the wheel the entrance of the weater must lie at some distace h_o below the surface of the water. The following equation may be used.

$$h_o = (1 + \alpha')\frac{C_h^2}{2g}$$

Where α' is the coefficient of discharge thru the rectangular orifiee and the discharge over the entrance spout.

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* John Smeaton, English Engineer is year 1752. Results of his experimant presented in Bulletin 529 of University of Wisconsin.

If the orifice is constructed with sharp edges and no obstructions the value of α' may be taken as .1 for a minimum value.

Having h_o, which locates the center of the entrance stream the approximate diameter of the wheel may be decided. It would be best to make the diameter an even number. Allow for clearance between bottom of the wheel and the tail water. Experiments at Wisconsin gave a serious decrease in efficienny when the wheel was subnerged in the tailwater. Around two inches is considered satisfactory for most conditions.

We are next concerned with the manner in which the water enters the wheel and how this entrance affects the shape of the buckets.

The water leaving the entrance spout will take a parabolic path. The vertex of this parabola will be the mid point of the stream where it leaves the spput. The construction of this parabola may be easily understood in the design of the laboratory experimental wheel, considered later on in this report.

To understand what happens when this parabolic stream enters the bucket let us consider three types of buckets (1) radically strait, (2) radically inclined, (3) theoretical correct shape.

Before considering these three types let us be sure that one point is clear. The wheel works by the weight of the water acting on the lever arm (radius of the wheel or a portion of the radius) from the time it enters the bucket until it leaves. It is evident then that our problem should be to get the water into the wheel at the highest point(a point wertically above the axle center). If the entrance is before or after this vertical line there is naturally a loss of energy. Also our problem is to keep the water in the buckets as long as possible- in other words delay the empting of the buckets until the lowest point is reached. Many men have the idea that the water upon entering the buckets should hit back of the buckets. This is not an impulse wheel and when an impulse does occur there is a serious loss in energy due to the incorrect bucket shape or incomplete filling of the buckets. This will be brought out in the following considerations.

(1) Radically strait (Fig 2)

From a study of Fig 2 it may be seen that the front of the bucket will strike the stream early thus preventing complete filling of the bucket. According to Bach for maximum efficiency the

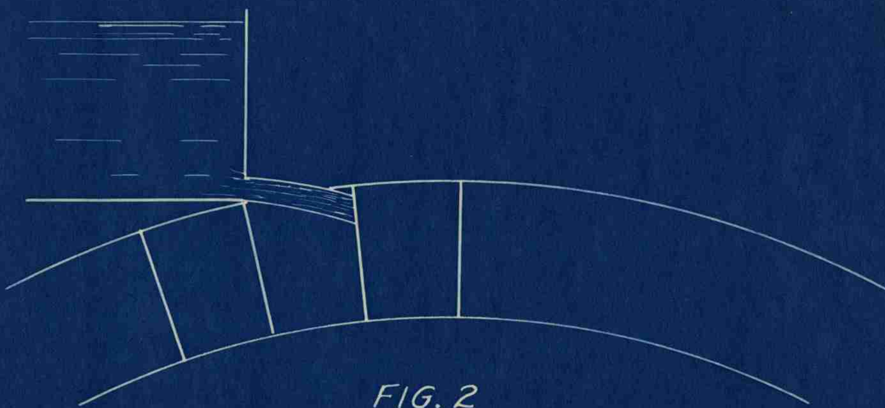


FIG. 2

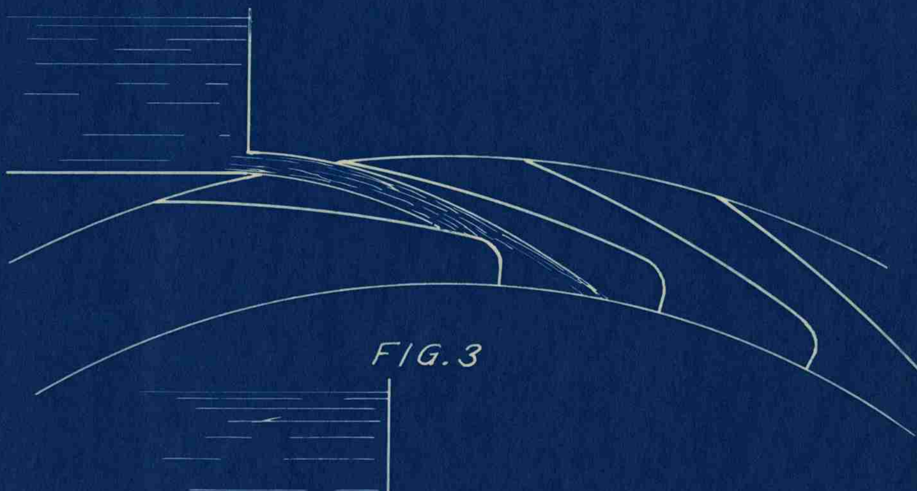


FIG. 3

FIG. 3A

bucket should be 1/4 to 1/2 full. Loss due to early exit of the water keeps the coefficient of filling very low. It is best to make the wheel wider to take care of the same quantity of water and not fill the buckets completely. Naturally the cost of the wheel will be a factor that must be considered.

It is also seen that the back of the bucket will receive an impulse from the stream thus increasing the energy. One must not be misled by this energy due to impulse. It is not large. It does not compensate for the other losses- particularly the loss due to early exit. The wheel is not an impulse wheel. It is not designed for that. If it was the entrance velocity should be considerable greater. The average entrance velocity represents only 1 or 2 feet of head. We get only a small part of this energy. The evidence is in the fact that the water still continues to move around after striking the bucket, indicating that kinetic energy is still present.

(2) Radically Inclined(Fig 3)

This shape bucket will also prevent proper filling. It will however prevent early exit of the water. They may be filled by having the entrance on the right side of the vertical line thru the axle and lower down(Fig 3A). This causes a serious loss, as already mentioned.

When entrance is at the highest point the back of the bucket strikesthe stream with a broad surface causing a serious loss.

(3) Theoretical Correct Shape.(Fig 4)

It must be kept in mind that while we have the path of the waterleaving the entrance spout the wheel is revolving with a peripheral velocity slightly less than the velocity of the water. Consider a particle of water in the center line of the stream and at the moment it enters the bucket at the circumference of the wheel. We are now interested in the path that this particle takes with respect to the wheel- the relative path of this particle. This relative path BN is shown in Fig 4. Curve B' N' is parallel with curve BN and tangent to the back of the bucket. The amount of water that will be subject to the back of the bucket hitting it is the amount entering along the arc B' C. This is a loss. To prevent this loss the bucket must be shaped according to the relative path. That would be the ideal bucket for the entrance. However the bucket should be inclined a little more to prevent early exit of the water. This added energy will offset the loss due to impact. Bach states that the bucket should not be inclined from the point B'(relative path) more than 1/2 of the bucket opening.

Figure 5 shows a crossection of the bucket when the stream has hit the back of the bucket and the front of the next bucket coming up has just touched the lower side of the stream, beginning to cut it off. A certain amount of air, entrapped in the space Z, will be compressed and will break through the stream causing squirting of the water. This causes a loss in energy due to loss of water

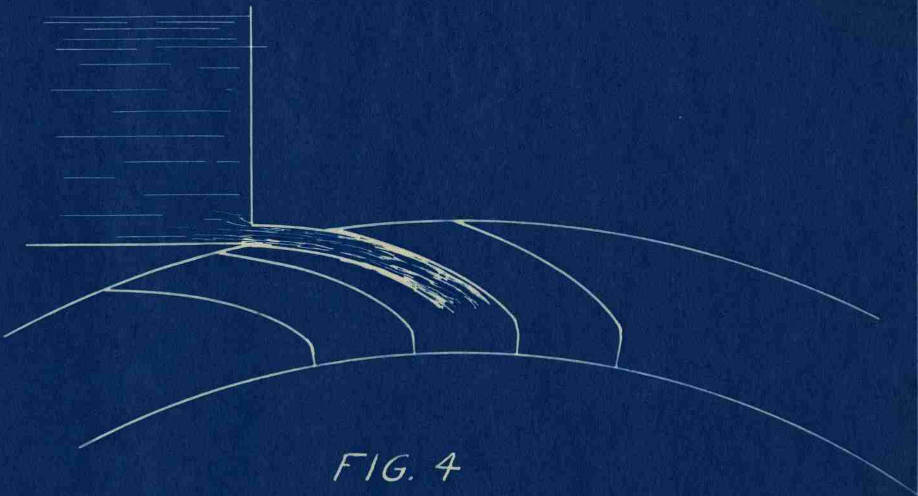


FIG. 4

FIG. 5

and insufficient filling. To prevent this the entrance stream should be made slightly narrower than the width of the wheel. This will allow any entrapped air to escape along the sides.

The Exit of the Water from the Wheel.

We have already mentioned the nature of the exit loss. This is the loss of some of the water spilling over the bucket before the bucket reaches the lowest point. In the average bucket this spilling of water takes place slightly past the horizontal line thru the axle, and increases until all the water has left the bucket at the lowest point. I believe it is clear to the reader that the greater the inclination of the bucket the smaller this loss would be. The manner of determinging this loss may be seen in the determination of the efficiency for the laboratory experimental wheel.

STEP NO. 2.

FOR

OBJECTIVE No. 1.

Design of the Laboratory Experimental Wheel According to the Theory

Requirements for the Wheel

1. High Speed Wheel

2. Entrance at Left of the Crown of the Wheel
   This is necessary in order to have the bucket filled at the uppermost point - a point vertically above the axis. Some difficulty may be encountered in getting the wheel to start by itself.

3. Data:

   Q = quantity of water = 310 gal/min = .7 cu.ft/sec.

   R = number of rev.min = 15

   D = diameter 6 feet.
   In this case the diameter is selected for its value in running the test and the arrangement in the laboratory. We are not interested in getting all the available power out of the water which will be located at a certain height above the floor.

   Na = theoretical power of the water experssed in horse power.

$$= \frac{62.5 \times .7 \times 7}{500} = .55 \text{ H. P.}$$

Determination of Bucket Dimensions

$$V = \frac{2\pi \text{ R. N.}}{60} = \frac{3.1416 \times 6 \times 15}{60} = 4.71 \text{ ft/sec}$$ = peripheral velocity of the wheel.

$C_h = 4.54\sqrt{4.71} = 9.9$ feet/sec = entrance velocity of the water.

$$\frac{C_h^2}{2g} = \frac{(9.9)^2}{64.4} = 1.52$$

α' = Coef of Discharge = .1 as minimum for carefully constructed outlets

Select $.12 = \alpha'$

$\alpha' \frac{C_h^2}{2g}$ = (head which must be used up in oversoming) (the friction thru orifice and spout)

$= .12 \times 1.52 = .183$ ft.

$(1 + \alpha') \frac{C_h^2}{2g} = 1.12 \times 1.52 = 1.70$ ft. = Location of the vertex of the parabola below water surface. The water upon leaving the entrance will take a parabolic path.

A = radical depth

$A = .368 \times \sqrt[3]{H}$ to $.553 \sqrt[3]{H}$

$= .368 \times \sqrt{8}$ to $.553 \sqrt{8}$

$= .736'$ to $1.106'$

A bucket with this depth would be too narrow. It would be best to select 5" or .416'

Take ϵ = Coefficient of filling of the bucket = 1/2

$Q = \epsilon\ a\ b\ v$

where q = quantity of water

a = radial depth

b = width of bucket

Substituting

$.7 = 1/2 \times .416 \times b \times 4.71$

$b = \frac{.7 \times 2}{.416 \times 4.7} = .72'$ = depth of buckets

The depth is too large in proportion to the width.

Select

$$4\ 1/2'' = .3751' = \text{radial depth.}$$

It is remembered that the more shallow buckets will have the center of gravity of the water farther from the center of the wheel and thus the lever arm will be greater. It also decreases the loss due to impact with the sides and bottom.

Substituting

$$b = \frac{2 \times .7}{.375 \times 4.7} = .8 \text{ feet}$$

The coefficient of filling was taken at the upper limit.

If we select 1/3

then

$$b = \frac{3 \times .7}{.375 \times 4.7} = 1.2'$$

Therefore best make the bucket dimensions as follows:

(4 1/2" = radial depth)

(1' = width of bucket

Determination of Width and Depth of Stream

For wheel without a middle partition the width of entrance stream = bo

$$bo = b - (2 \times .656) \text{ to } b - (2 \times .328)$$

$$= b - 1.312 \text{ to } b - .656$$

This apparently will not work for small wheels.

Select width $= bo = 10"$

So = Depth of stream

$$So = \frac{Q}{bo\ Ch} = \frac{.7}{.83 \times 9.9} = .085' = 1.02"$$

Drawing the Center Line of Entrance Stream

and

Location of the Center of the Wheel

Allow 2" for clearance (x") between wheel and the tail water.

Assume (Xo) vertical clearance between the spout and the circumference of the wheel = 3/8" = .0310'

In this particular case where we are not limited in the head, it is best to proceed on the drawing board and by trial determine the location of the center of the wheel so that the entrance of the stream is to the left of the crown of the wheel. We will endeavor to have the point S_1 perpendicular from the crown (as high in the wheel as possible) or slightly to the right of hhe crown. The point S_1 is the point where the discharge water strikes the bucket. It is the intersection of a curve connecting the center of gravity of the water in the buckets and the relative curve of the center of the entrance stream.

The first step is to draw the center line of the stream(ABB') discharging from the orifice or sluice (Fig 6). This will be a parabola. The construction of this parabola will how be taken up in detail.

$$h_o = (1 + \alpha')\frac{D_h^{\ 2}}{2g} = 1.70 \text{ feet}$$ = Location of vertex of parabola below water surface. That will be the center of the entrance stream

S_o = 1.02' = .085' = vertical depth of the entrance stream

X_o = 3/8" = .031' = vertical clearance between the spout and circumference of the wheel.

Draw these on the board.

Locate the focus of the parabola = $\frac{C_h^2}{2g}$ below the vertex

$$\frac{C_h^{\ 2}}{2g} = 1.52'$$

Consider the vertex of the parabola as point A. Lay off arbitrary points 1,2,3,4,5, etc., vertically upward from point A. Lay these same points 1,2,3,etc., vertically downward from point O. Lay off horizontal lines thru the lower points. With the focus as a center describe an arc from the upper point No. 1 to where it cuts the horizontal line thru lower point No. 1. This intersection is a point on the parabola. Do the same for point 2,3,etc..

It would be best to proceed by determining the value of Y for entrance of the water at the crown and then increase this value for trial. Y is the horizontal distance between the orifice entrance and the center of the wheel.

$$Y = \sqrt{2p}\sqrt{-R + M - P + \sqrt{2RM - M^2 - (R - M + P)^2}}$$

In which R = radius of thw wheel = 3 feet

$2P$ = parameter of the parabola(entrance stream)

$$2P = \frac{4\,C_h^2}{2\,g} = 4 \times 1.52 = 6$$

$$P = 3$$

M = vertical distance between wheel and the center line of the stream.

$$M = \frac{So}{2} + T + Ko$$ where T = thickness of spout

$$= \frac{085}{2} + 02 \quad 03$$

$$= .042 + 02 + 03$$

$$= .092$$

Substituting

$$Y = \sqrt{6}\,\sqrt{-3 + .09 - 3 + \sqrt{6 \times .09^2 + (3-09+3)^2}}$$

$$= \sqrt{6}\,\sqrt{-5.91 + \sqrt{.54 - .0081 = 35}}$$

$$= \sqrt{6}\,\sqrt{-5.91 + \sqrt{35.5}}$$

$$= \sqrt{6}\,\sqrt{-5.91 + 5.95}$$

$$= \sqrt{6}\,\sqrt{.04}$$

$$= 2.45 \times .2 = .4.90' \text{ or appr. } 51'$$

$$= 6''$$

Take this value as first trial and draw in the outline of the wheel(inside and outside circumference)

It is evident on the drawing that the stream will enter at the crown of the wheel and this offers a check on the above calculations.

We desire entrance at the left of the crown so that S_1 will be near the perpendicular from the crown.

Select

9" ad an arbitrary value of Y

Drawing this(Fig 6) it appears that S_1 may be located approximately right. The curve thru the center of gravity is estimated. Accuracy on this point is not essential and does not warrant precise calculations. We are merely trying to get S_1 as high as possible in the wheel. When it is near the crown small change has little effect. This is particularily true on the large wheels.

Relative Path of the Entrance Stream

The next step is to draw the relative path (BN) of the water entering the wheel. See Figure 6.

The Horizontal component (C_h) of the absolute velocity with which the water enters the bucket is a corstant.

A particle of water in the center of the stream traverses a distance C_hT in a horizontal direction in an element of time T.

D_h = 9.9 feet/sec(previously determined)

Select element of time = .01263 sec.

9.9 x .01263 = .125 feet = 1 1/2"

Lay this distance off to the right on the horizontal line thru the point where center of stream cut the wheel circumfereme so that

$B\ B_1 = 1\ 1/2" = B_1\ B_2 = B_2\ B_3 = B_3\ B_4$ etc.

Draw thru these points $B_1\ B_1\ B_2$ vertical lines until they intersect the center line of the stream. This intersection(1,2,3 etc.) will be the position of a particle of water at the end of each consecutive .01263 seconds. Remember that C_h was horizontal component of the velocity of the water entering the wheel.

Describe thru these points(1,2,3 etc.) arc's if a circle about the center of the wheel (M). Points on the relative path of the water entering the wheel will lie somewhere to the left on these arcs.

Draw thru these same points(1,2,3 etc) lines from the center of the wheel until they cross the outer circumference of the wheel. Along the outer circumference of the wheel and to the left is laid off a distance equal to 1 x V x T from the first point(at the end of 1st .01263 second) 2 x V x T for second point, 3 x V x T for third point etc.

1 x V x T = 1 x 4.71 x .0126 = .059' =	.708	inches
2 x V x T =	1.416	"
3 x V x T =	2.124	"
4 x V x T =	2.832	"
5 x V x T =	3.540	"
6 x V x T =	4.248	"
7 x V x T =	4.956	"
8 x V x T =	5.664	"
9 x V x T =	6.372	"
10 x V x T =	7.08	"
11 x V x T =	7.8	"

From these points on the circumference, lines are drawn to the center of the wheel. These lines crossing the arcs that were drawn above will locate points on the relative path(BN) of the center line of the stream.

Determination of Number of Buckets

The water entering at the circumference of the wheel occupies a certain length of arc on the circumference. The upper and lower limits of the entrance stream may be drawn in parallel to the center line of the stream previously laid out as a parabola. The length of entrance arc (CBD) may then be determined by scaling the drawing.

$$\text{CBD} = \text{entrance arc} = 4\ 1/2'' = .375'$$

The width of bucket opening = e

$$e = \frac{4}{3}\ \text{CBD} \quad \text{to} \quad \frac{3}{2}\ \text{CBD}$$

substituting $e = \frac{4}{3}\ .375$ to $\frac{3}{2}\ .375$

$$e = .5' \quad \text{to} \quad .562'$$

Select .524' as width of bucket opening(Select this value so that the number of buckets will be even)

This distance = EO in Fig 6

$$\text{Number of buckets} = Z = \frac{2\pi R}{}$$

$$= \frac{2\pi 3}{.524} = \frac{18.85}{.524}$$

$$= 36 \text{ buckets}$$

Determination of Bucket Curve

The bucket curve for the entrance of the water should be shaped according to the relative path. This was previously discussed in the theory. The loss at exit is much more inportant than any loss at entrance therefore select the curve now for the exit loss. The bucket curve should be tangent to the relative path of the stream near its base and displaced to the left of relative curve at the circumference of the wheel, not more than 1/2 of the bucket opening CO.

CO = Bucket = .524 or practically 6 inches.

Therefore displacement to left should not be more than 3"

Select 2 1/2" for this displacemtnt.

The bucket curve may be laid off by the method recommended by C. M. Sames in the chapter entitled " Water Wheels" in the Mechanical Engineer's Handbook (3rd Edition) by Lionel S. Marks.

The radial piece of the bucket is to be made of a strait piece. it should equal 1/3 of the radial depth.

1/3 x 4 1/2" = 1 1/2"

Lay off this 1 1/2" on a radial line so that the outer end of the 1 1/2" will just touch the relative path, point N'

Drop a line from point E, $10^\circ - 15^\circ$ with a radial line thru point E, Select a center on this line for the bucket curve so that the curve will pass thru E and be tangent to relative path near radial piece. Round this curve into the radial piece.

For a homemade bucket with strait sides it seems reasonable to connect point E with the intersection of radial piece and the relative path(Point N'). This type of bucket is shown in Fig.4 in addition to the curved bucket.

The dimensions for the bucket may be laid off on the side pieces of the wheel by the following method.

(1) Lay off the radial lines for bottom of bucket at distances of .524' on the outer circumference of wheel or .458 = 5.5" on the inner circumference of the wheel.

The inner radius of the wheel = 2.625'

(2) Measure off the length of 1 1/2" on these radial lines from the inner circumference.

(3) Lay off point (E) 9 3/4" from the intersection of line on the outer circumference. The value of 9 3/4" in secured by scaling the drawing.

(4) Connect point A and the outer end of the 1 1/2" mark (Point N')

Length of the bottom of the bucket = 1 1/2"

Length of the side of the bucket = 9 3/4"

Determination of the Theoretical Efficiency of the Wheel

The efficiency of this wheel designed for the laboratory experiments can best be arrived at by determining all of the energy losses. These energy losses may be classigied as (1) Energy Losses at Entrance.(2) Energy Losses at Exit(3) Energy Loss Due to Friction in Bearing (4) Energy Loss Due to Eindage.

We will first make a few calculations necessary in determining the classified energy losses.

Number of buckets cutting stream per second = $\frac{ZN}{60}$

Where Z = No. of buckets

N = R. P. M.

Substituting $\frac{ZN}{60} = \frac{36 \times 15}{60} =$ 9 buckets cutting stream per sec.

Vol. of water contained in one bucket $= Q = \frac{Q}{\frac{ZN}{60}}$

Substituting

$$Q = \frac{.7}{9} = .077 \text{ cubic feet of water in each bucket}$$

The crossectional area of the water in the bucket = $f = \frac{Q}{b}$

Where b= width of bucket

Substituting $f = \frac{.077}{1} = .077$ sq. feet

R_s is the radius representing the distance the center of gravity of the water in the bucket is from the cneter of the wheel. This will be the lever arm for the weight of the water. The point S_1 (Fig 6) is where the radius R_s intersects with parabola path of the water leaving the entrance spout.

$$R_s = \sqrt{(R-a)^2 + \frac{qz}{2\pi b}}$$

Substituting

$$R_s = \sqrt{(3 - .375)^2 + \frac{.077 \times 36}{2 \quad \times 1}}$$

$$= \sqrt{(2.625)^2 + \frac{2.77}{6.28}}$$

$$= \sqrt{6.89 + .44} = \sqrt{7.33}$$

$$R_s = \sqrt{7.33} = 2.71 \text{ feet}$$

With this as radius about center M. locate point S_1 in Fig (6)

Draw S_1 S_4 = C_h = 9.9 feet = horizontal distance

Draw thru S_1 a line tangent to the parabolic entrance curve.

Draw thru S_4 a vertical line. Where it crosses the tangent line is point S_5. S_1 S_5 is the absolute velocity of the stream at the point S_1. Lay off S_6 S_7 = 4.71' = peripheral velocity of wheel at point S_6. Point S_6 is where the R_s cuts the outer circumference of the wheel. Peripheral velocity at point S_1 = S_1 S_8. S1 S_8 is part of radius through point S_7.

Connect S_8 and S_5.

This distance(S_8 S_5) is equal to the relative velocity of the water at the point S_1 = W_1 = the relative velocity of water just before it strikes the bucket.

Scaling the drawing we get:

$$W_1 = 7 \text{ feet/sec.}$$

(1) Energy Loss at Entrance

(a) Loss due to the frictional resistance thru the orifice and on the entrance spout = he'

$$he' = \alpha' \frac{C^2_h}{2g}$$

Substituting = .12 x 1.52 = .183 feet

(b) When the shape of the bucket does not conform to the relative path of the water there is a loss due to the back of the bucket hitting the stream = he"

$$he'' = \left(\frac{\overline{EF}^2}{2g} + \frac{RL^2 - RK^2}{2g}\right)\left(\frac{BE}{OE}\right)$$

Fig 6 A shows the position of the strait sided bucket when it first touches the underside of the stream. All points are given the same letters as Fig 6. A line parallel with the relative path should be drawn where it is tangent to t he back of the bucket. In this case it will be the same as the relative path at the center line of the stream. The amount of water subject to impact is the water entering along the arc BE(When the point E of the bucket arrives at lower part of the stream). Therefore the amount of water subject to impact will equal to $\frac{BE}{OE}$.

This energy lost can best be arrived at by constructing the parallelogram of velocities. The point for constructing the velocities should be taken at a point midway of the arc EB. Drawing thru this point a line parallel with the relative velocity BT and where this line curs the bucket outline(point R) construct the parallogram.

Draw R v perpendicular to radius thru R and equal to the peripheral velocity of wheel at this point. This may be laid off graphically by laying off S_6S_7 = 4.71 feet/sec

Draw R S_5 = the absolute velocity of the stream at this point.

Draw this parallel to a line tangent to t he entrance stream at this point. Construct the parallologram RVS_5E.

Now draw R F which is the extension of the back of the bucke t.

This is the path which the water is allowed to take.

E F is drawn perpendicular to R F and represent lost energy.

This lost energy = $\frac{EF}{2g}$

Now construct a new parallelogram with RF and RV

The distance RL represent the absolute velocity after impact. The distance RS_5 represents the absolute velocity before impact. Therefore the increase in kinetic energy due to the back of the bucket hitting the stream will equal

$$\frac{\overline{RL}^2 - R\overline{LS_5}^2}{2g}$$

This energy may be considered lost since it will soon hit the bottom of the bucket.

Therefore the total energy lost:

$$he'' = \frac{\overline{EF}^2}{2g} \quad \frac{\overline{RL}^2 \quad \overline{RS_5}^2}{2g} \quad \frac{BE}{OF}$$

These values may be determined by scaling:

Substituting

$$he'' = \left(\frac{\overline{.7}^2}{64.4} + \frac{\overline{10.5}^2 - \overline{10.25}^2}{64.4} \right) \frac{2.5}{6}$$

$$= \left(.0076 + .080 \right) \frac{2.5}{6}$$

$$= .0876 \times \frac{2.5}{6} = \frac{.219}{6} = .036 \text{ feet}$$

This loss is very small and for all practically purposes need not be sonsidered or even figured for any waterwheel. The strait sided bucket does not affect this loss to any degree.

(c) There is a loss of energy due to the impact of the water against the bottom of the bucket = he"

$$he''' = \frac{W_1^2}{2g}$$

Substituting $$= \frac{7^2}{64.4} = .76 \text{ feet}$$

Taking a summation of loss of energy at the entrance

$$he' + he'' + he'''$$

$$.183 + .036 + .76 = .979' \text{ feet}$$

Nearly 1 foot of the total head will be used up in overcoming the entrance losses.

(2) Energy Losses at Exit

In fig 6 lay off E E_1 so that the area between this line and bucket outline is equal to f = .077 sq. ft. Do this by trial. Put thru this line a radius so that it is perpendicular. Then E_1 E'_1 will equal the distance above bottom of the wheel when the bucket first begins to spill E_2 E'_2 is distance when half of the water is lost. E_3 E_3 represents the distance when all the water is lost.

Then the loss due to early exit = ha'

$$ha' = \frac{E_1E_1' + E_2E_2' + E_3E_3'}{6}$$

Substituting $$= \frac{7.8" + 4 \times 5.5" + 3.5"}{6}$$

$$= \frac{.65 + 4 \times .4^{2}6 + .3}{6}$$

$$= \frac{.95 + 1.84}{6} \quad \frac{2.79}{6} = .46 \text{ feet}$$

Total loss at exit

$$ha = ha' + \frac{V^2}{2g} + X''$$

X'' = distance between bottom of the wheel and the tail water.

This loss will not be considered in this experimental wheel. There will be an unusually large clearance and all calculations will be made with the bottom of the wheel as the reference line. The loss $\frac{V^2}{2g}$ is the absolute velocity with which the water leaves the wheel.

Substituting $$ha = .46 + \frac{4.71^2}{64.4}$$

$$= .46 + .34 = .80 \text{ feet}$$

(2) Energy Loss Due to Friction in the Bearings

The bearings are anti-friction bearings and so it is difficult to estimate the friction loss. It will be less than 1/2%.

(3) Energy Loss Due to Windage

This can be neglected since the speed is very slow.

Summation and Guaranteed Efficiency

Summation of Energy Loss = .979' + .80 feet = 1.779 feet

Total Head of water considering bottom line of wheel as reference = 1.70' + 6' = 7.70 feet

$$\frac{1.779}{7.70} = .23 \text{ or } 23\% \text{ loss}$$

23% + 1% (for friction)= 24%

Efficiency = 100 - 24 = 76%

Allowing 5% for a factor of safety the guaranteed would be:

$$.95 \times .76 = 72.2\%$$

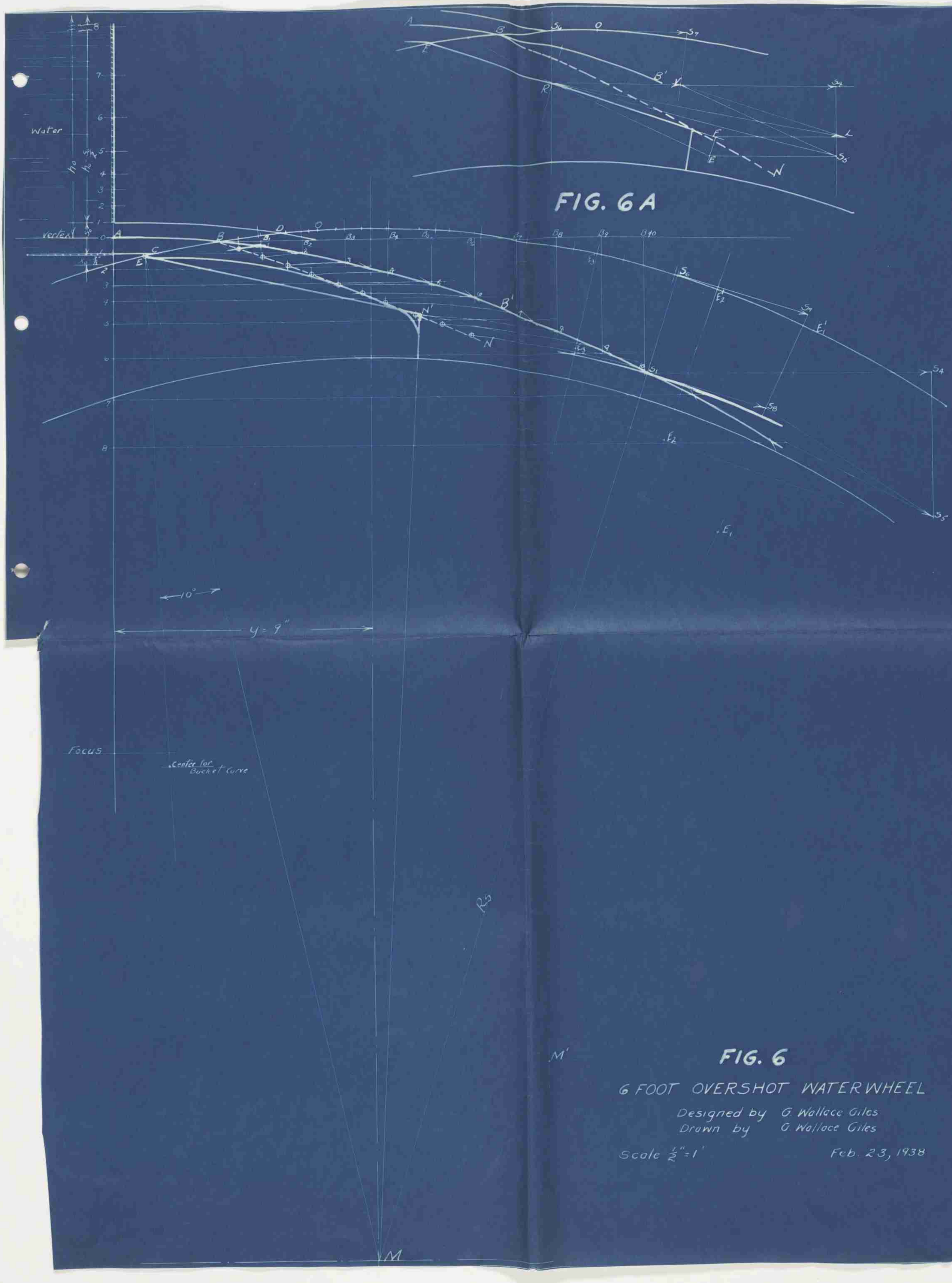


FIG. 6

6 FOOT OVERSHOT WATERWHEEL

Designed by G. Wallace Giles
Drawn by G. Wallace Giles

Scale 1/2" = 1'

Feb. 23, 1938

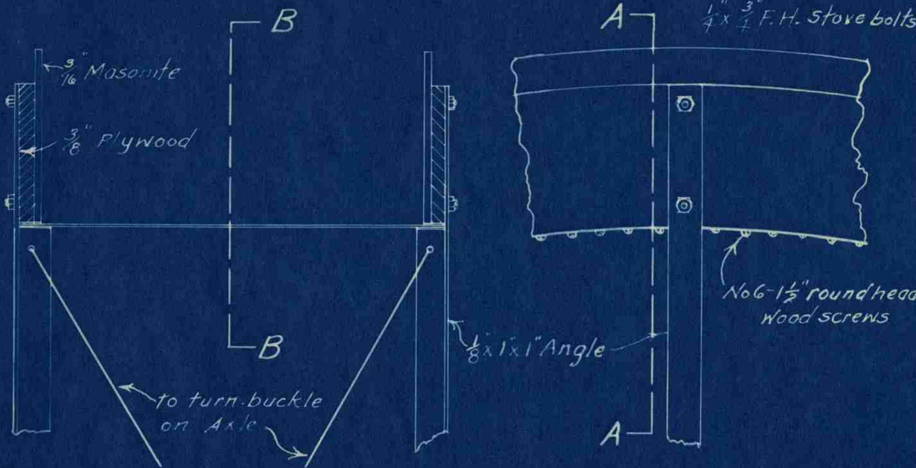
STEP NO. 3

FOR

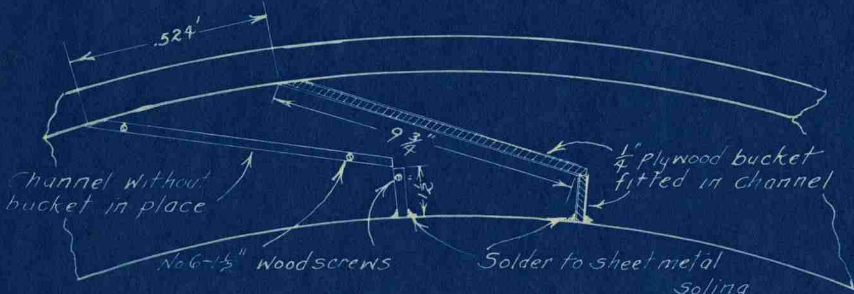
OBJECTIVE NO. 1

" Construction of the Experimental Wheel and Description of the Laboratory Apparatus "

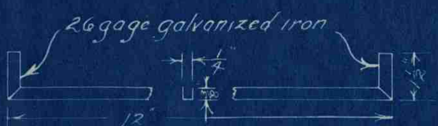
The construction features of the 6 foot overshot water wheel are shown in the detail drawing Fig. 7. The sides are constructed of a thickness of 3/16" masonite and a thickness 3/8" plywood. Half circles are cut from large sheets of 3/16" masonite and 3/8" plywood. These half circles are tacked together with the joints spaced 90 degrees apart. The masonite circle is put on the inside since it is waterproof. The outer diameter of the masonite circle is 6' - 2" which allows a 1" shroud. The plywood is placed on the outside and has an outer diameter of 6' which represents the true diameter of the wheel. The spokes of the wheel are of 1/8" x 1" x 1" angle iron and are bolted to the circles with 1/4" flat headed stove bolts. The soling is of 26 gage galvanized iron 13 1/2" wide. This permits an inside diameter of 12". 1/4" x 3/8" x 3/8" channels made of 26 gage galvanized iron are used to hold the radial portion of the bucket. These are soldered to the soling before it is screwed to the inner circumference of the sides. Asphalt paint is used between the sides and the metal soling to make it leak proof and to protect the plywood from water. The end pieces of the channel are next screwed to



Section A A



Section B-B



Channel to carry Radial Bottom

FIG. 7
OVERSHOT WATER WHEEL
Scale 1/4" = 1"

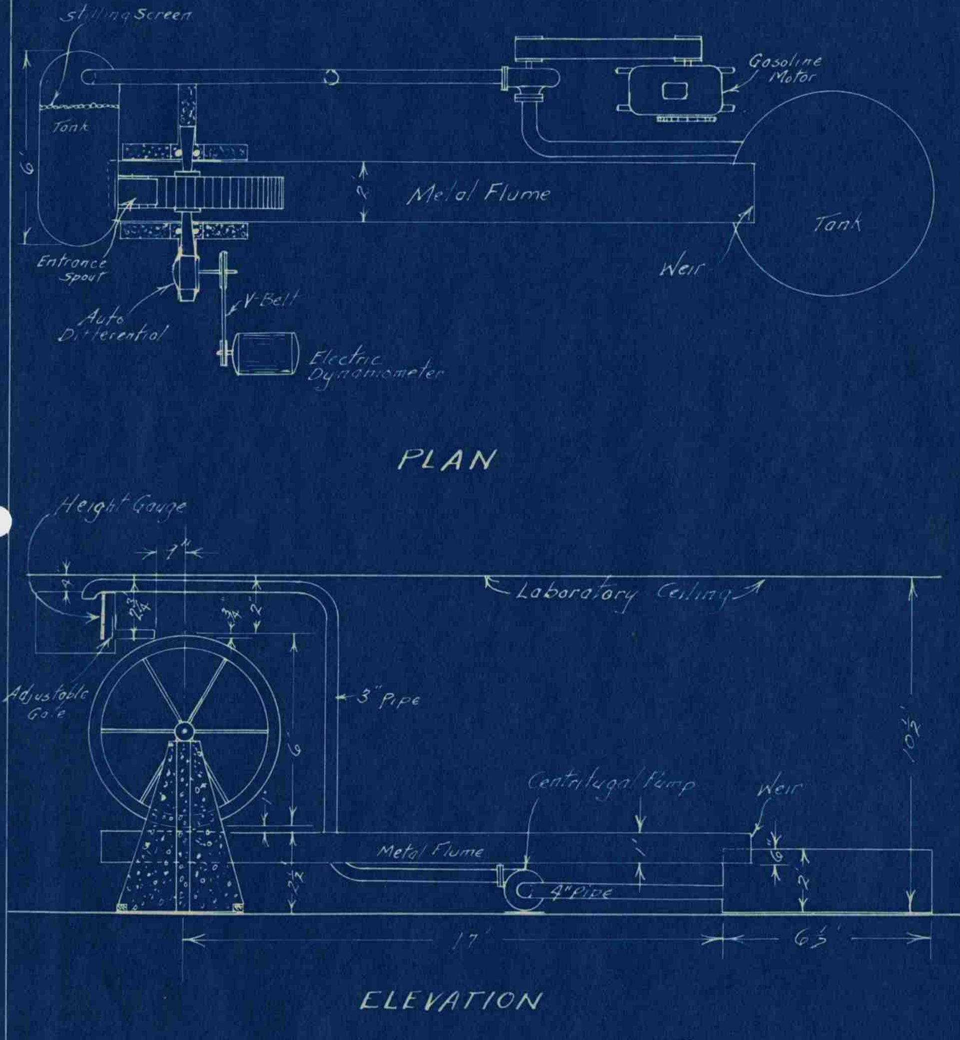


FIG. 8
Schematic Drawing
Overshot Water Wheel Arrangement

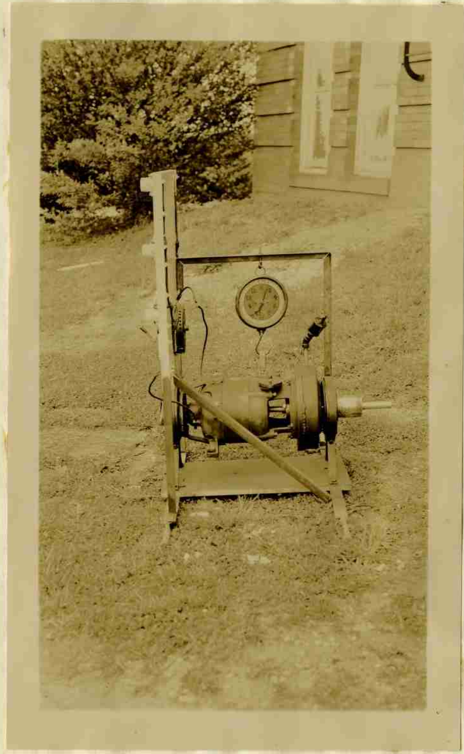
the sides with No. 6- 1/2" flat headed wood screws. 9 3/4" lengths of the light channel are screwed to the sides to hold the radial pieces of the buckets. The buckets are made of 1/4" plywood painted with asphalt for waterproofing.

The wheel is built on the rear axle assembly of an automobile. The axle and housing are cut about 1/3 of the distance from one end. The two ends are mounted on 5' 7" concrete pedestals facing each other. The wheels are removed from the brake drums, and the spokes of the water wheel are bolted in their place.

The general arrangement of the apparatus for conducting the tests is shown in Figure 8. An 18" V- pulley is mounted on the propellar shaft of the differential and is belted to a 1 1/4" V-pulley on an electric dynamometer. The differential gear ratio is 1 to 4, and the pulley ratio will be 1 to 15. The tôtal spped increase will be 60 times. The dynamometer has a 1 K.W., 32 volt D.C. shunt would generator with a rated R.P.M. of 1200. The R.P.M. at which it will be driven will ba about 900 R. P. M. The load may be more accurately controlled by using a lower speed and consequantly a lower voltage.

The theoretical output of the wheel is only .55 H. P. The load will be controlled by a bank of 32 volt light bulbs, wired in parallel.

A 3" contrifugal pump with a rating of 300 G.P.M. at 870 R. P.M. will be used to curculate the water from a lower tank, with a capacity of 540 gallons to an upper tank with a capacity of 180 gallons.



Dynamometer Built For Measuring The Power Output

of The Waterwheel.

A gasoline motor will be used to drive the pump. A valve in the discharge pipe line of the pump will be used to control the amount of water supplied to the upper tank. A stilling screen near the entrance of the water into the upper tank will prevent too great a disturbance of the water at the gate opening. A glass gauge attached to the tank near the gate will indicate the height of the water in the tank. It will be graduated to read the head of water on the wheel.

The datum line will be the tangent to the lowest point of the wheel buckets. The bottom of the gate opening lies at a vertical distance of 3/4" below the crown of the wheel.(neglecting the 1" shroud). The gate is adjustable for varing the depth of the entrance stream. A horizontal rectangular sluice 15" long carries the stream to the wheel. The stream will enter the buckets at a point 9" horizontally from the center of the wheel.

The water is discharged from the wheel into a rectangular metal flume 1' deep and 2' wide. This carries the water 17' horizontally to the lower tank. The water enters the tank through a rectangular weir, which will be used to measure the quantity of water used by the wheel.