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Some Recent Tests of High-Power, High-Speed Water Turbines

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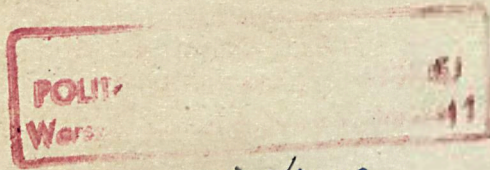
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Some Recent Tests of High-Power High-Speed Water Turbines

Investigations at Holyoke Flume Show That Wheels for Very High Speed-Power Values Can Be Designed with Good Efficiencies

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DURING the last few years a large number of tests have been made in the Holyoke testing flume on wheels of high "type characteristics,"* that is, on wheels of high speed and power values. The results of some of these tests are noteworthy as demonstrating a remarkable progress in the art of designing and building these wheel types and as proving that some of the current adverse opinions regarding the possibility of such progress and of further important developments in the field of such wheels were erroneous or, at least, too pessimistic.

*The type characteristic, called by some engineers also the specific speed of a wheel, is the product of the speed in revolutions per minute and the square root of the power of the wheel, both under 1 ft. of head. It is expressed by the formula $K_t = N_1 \sqrt{HP_1}$.

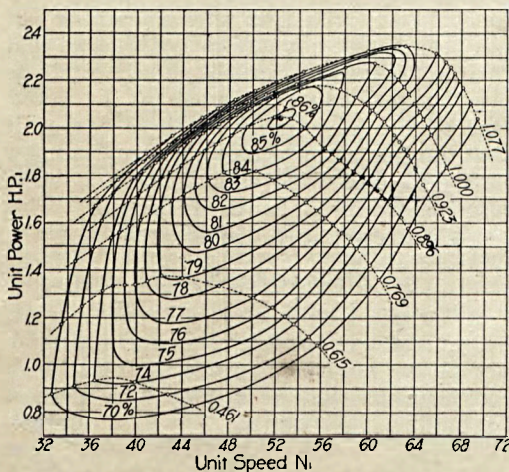


FIG. 1—HOLYOKE TEST RUNNER 1796

Diameter, 28 in.
Best efficiency, 86.2 per cent.
Normal speed, 52.2 r.p.m.
Normal power, 2.04 hp.
Normal K_t , 74.5 (specific speed).
Designer, C. W. Larnier.

The most important of these opinions were:

1. That it was impossible to obtain equally or even nearly as high efficiencies with wheels of high as with those of relatively low type characteristics, and

2. That attempts to increase the speed and power value any appreciable amount above those obtained with the best known American standard wheels (Smith, Samson, Victor and others) would necessarily result in pulling down the efficiency to values which would make the wheel uncommercial.

3. That it was impossible to obtain great overloads with high type characteristic wheels, or in other words, that if their load was increased even slightly above normal the efficiency would drop off rapidly and the wheel would be "overgated" very soon. It was thought that when a wheel of high type characteristic gave an overload of say 8 per cent it was quite satisfactory.

4. That with reduced load (part gate) the efficiency would fall off very rapidly and that the entire load-efficiency curve tended to be very unsatisfactory.

5. That the speed-efficiency curve was also unsatisfactory and that, therefore, high type characteristic wheels were not commercial under variable heads.

6. That in general the operating characteristics of these high-power wheels could not be controlled and regulated by the designers as well as those of low-power and low-speed types.

THE LARNER TESTS

The last complete account and discussion of a series of Holyoke tests was given by Chester W. Larnier in his paper read before the American Society of Civil Engineers October, 1910. (See "Transactions," Vol. 66, page 306.) With one of the five wheels, all of which were of his own design, namely,

with the wheel bearing the test number 1796, he set a new mark in the development of high speed, high-power wheels having exceeded the speed and power values of the best known American standard wheels, which held the record of having gone

power values, that is, the speed, discharge and power, reduced to 1-ft. head (columns 7, 8 and 9). We then plot the power and efficiency values into curves using the speed as abscissæ and obtain thus for each gate opening at which the turbine was tested a

PART OF HOLYOKE TEST REPORT ON TURBINE 1796, MADE FEB. 25, 1909

1	2	3	4	5	6	7	8	9
Gate opening	Head, H , in ft.	Speed, N , in r.p.m.	Discharge, Q , in sec.-ft.	Brake horsepower	Efficiency, per cent	$N_1 = N/\sqrt{H}$	$Q_1 = Q/\sqrt{H}$	$\frac{Hp_1}{H\sqrt{H}}$
1.077	17.11	153.00	97.00	125.20	66.52	37.00	23.45	1.76
1.077	16.99	199.67	101.16	147.66	75.84	48.50	24.55	2.10
1.077	16.94	224.33	102.93	156.33	79.04	54.60	25.00	2.25
1.077	16.89	239.33	104.50	159.58	79.72	53.20	25.40	2.30

furthest of all in this direction and of having gone "about as far as one should attempt to go."

It is proposed in this article to put on record some of the Holyoke tests made after test 1796 and to show what further progress has been made in the design of high-power wheels and to what extent the adverse opinions mentioned above have been proved erroneous or too pessimistic.

As space forbids giving the complete test reports of these wheels to be mentioned, their characteristics will be shown by curves drawn with greatest accuracy from the reported test values. For some wheels the "equal-efficiency curves" which show at a glance the behavior of the wheel under any conditions of speed and power will be given, whereas, for other wheels, to save space, only three curves will be given, one in each of the last three figures, showing the efficiencies at three different speeds plotted against power.

The "equal-efficiency curves" are equivalent to the contour lines of a topographical drawing representing a hill, showing instead of points of equal elevations points of equal efficiencies. As the efficiency is a function of two variables, speed and power, we may speak of an "efficiency hill" or an "efficiency surface."

METHOD OF DRAWING CURVES

The method of drawing these curves is very simple. From the principal data, copied from a Holyoke test report (see columns 1 to 6 of the table, which gives a part of the test report for wheel 1796) we compute the unit speed discharge and

speed-power and a speed-efficiency curve. From the speed-efficiency curves we find the speeds at which with the different gate openings the same efficiencies are obtained, and mark these speeds on the corresponding speed-power curves (which we draw in dotted lines on a new sheet). Then we draw a continuous curve through the obtained points. We do the same with the other efficiencies, drawing curves which must apparently resemble each other and change gradually one to the other. If any smoothing out is necessary, in order to correct errors of readings, this can now be done in the most rational way, but in order to avoid any criticism this smoothing out has been avoided, wherever possible, so that the curves given represent as accurately as possible the values reported by the flume. One of the advantages of these curves is that the real point of best efficiency can now be determined with almost absolute accuracy as the peak point of the hill. This point is marked by a double circle.

FIRST IMPROVEMENT

After the results of Mr. Larner's wheel 1796 became known the other turbine builders set to work to improve their turbines, making, however, no attempts to increase the power-speed values. The first company to report considerable improvement was James Leffel & Company, of Springfield, Ohio, which had obtained with an improved design of their Samson wheel an efficiency of 90 per cent. The curves of this wheel are given in Fig. 2. Remarkable is the broadness of these curves, indicating the great adaptability of the wheel to varying

conditions of operation and particularly to varying loads. This fact is the more notable as the maximum efficiency also reached values which until very recently were thought impossible with wheels of high speed and power. At about the same time the S. Morgan Smith Company improved their Smith wheel (original test 1511), increasing its efficiency from 86.3 to 88.1 per cent. The three curves of this wheel (No. 1895) are given in Figs. 8, 9 and 10.

In March, 1911, the test on the author's 12-in. wheel, which formed the basis for his later wheel designs, was made in Holyoke. The wheel was designed to prove the author's belief that by using correct proportions the speed and power values could be increased considerably and still a thoroughly commercial wheel obtained, without deviating from the generally adopted shape of runner.

The best efficiency was 83.7 per cent. It was obtained with a speed of 122 and a power of 0.46 (type characteristic 82.8). Reducing the power value to a wheel diameter which would give the same best speed as wheel 1796, namely, 52.5, we would obtain $(122/52.5)^2 \times 0.46 = 2.57$ as against 2.03, or an increase of 23 per cent. The efficiency of the wheel, considering its small size, was very satisfactory, for it is a fact, established by theory (see Professor Camerer's article in the "Zeitschrift des Vereins Deutscher Ingenieure" of Sept. 18, 1909) as well as by experiment, that the efficiency of turbines depends on their sizes.

According to the information obtained from H. F. Sickman, chief engineer of the Holyoke Water Power Company, the Holyoke tests show that a model wheel as small as the author's would always have from 2 to 3 per cent less efficiency than the usual sizes (say 30 to 36 in.) that are tested in the flume. This was in fact shown to be true when a 30-in. wheel of exactly the same design was tested (No. 2060). This wheel was built by the Allis-Chalmers Manufacturing Company from drawings submitted by the author and tested in September, 1911.

Fig. 3 shows the curves plotted from the test report. We see that an efficiency of 87.2 per cent was obtained with a speed of 49

and a power of 3.18 (type characteristic 87.4). The general characteristics of this wheel are in spite of its greater speed-power values and higher best efficiency no worse than those of test 1796; as a matter of fact this wheel is even somewhat more "flexible," thus furnishing a convincing proof that we were altogether too prejudiced in our opinions about further possibilities in the design of high-power wheels.

THE AUTHOR'S LATER WHEELS

Besides this wheel three other runners, designed by the author and built by the Allis-Chalmers Manufacturing Company, were tested. In designing these wheels the following specifications were to be followed:

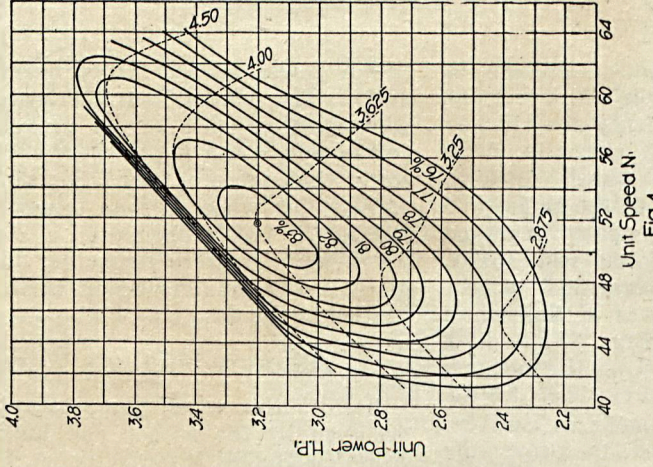
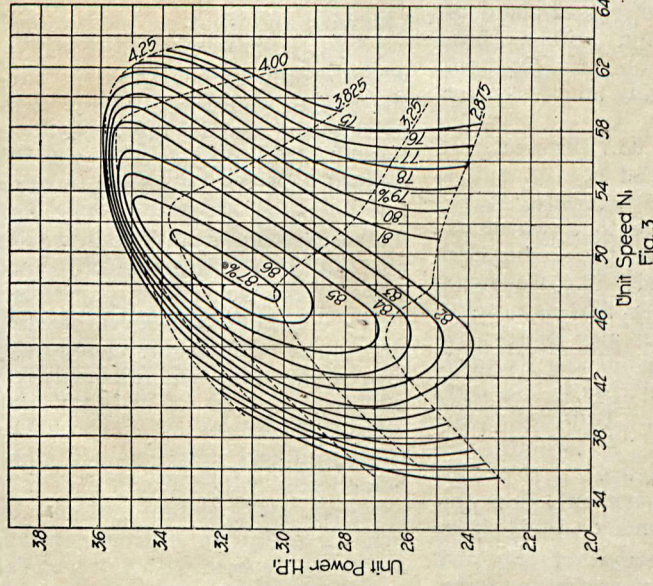
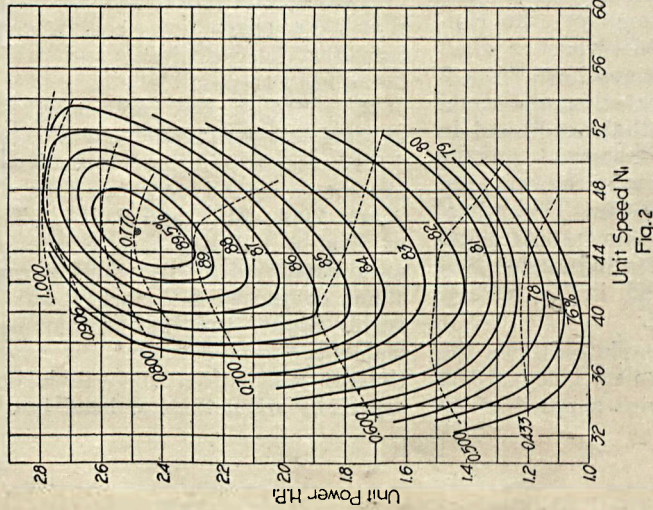
1. To increase the speed of the original wheel simply by changing the curvature of the runner vanes only at the entrance and leaving the rest of the bucket vanes unaltered. Nothing specific was thus prescribed, and the design was made primarily for purposes of study. The author predicted that this modification would have the effect of increasing the unit power of the wheel if the wheel be overspeeded.

2. To modify the curvature of the runner vanes, without any changes in the general proportions and dimensions with the purpose in view of raising the best efficiency, the condition, however, being that the speed and power values must not fall below those which would give a type characteristic of 78 at best efficiency.

3. To design an entirely new runner with a new guide case with the purpose in view of raising the power and speed values so that a type characteristic of 90 would be obtained at best efficiency and the efficiency be as high as possible.

In all cases the same draft tube and general test arrangement was to be used.

The results obtained with these wheels are shown by the curves of Figs. 4, 5 and 6 (tests 2068, 2121 and 2122). The curves of Fig. 4 indicate that what the author anticipated with his wheel 2 came true. When overspeeded the wheel has a considerably higher unit power than under normal speed. This makes the wheel exceptionally well suited to variable heads, and especially when the low head is very much



FIGS. 2-3-4—CHARACTERISTIC CURVES PLOTTED FROM TEST REPORTS OF THE HOLYOKE TESTING FLUME

	Fig. 2	Fig. 3	Fig. 4
Test, number	1900	2060	2068
Diameter, inches	35	30	30
Best efficiency, per cent.	90	87.2	83.2
Normal speed, r.p.m.	45.3	49.0	51.8
Normal power, hp.	2.48	3.19	3.20
Normal K _t (specific speed)	71.3	87.4	92.8
Designer	Samson	Zowski, I	Zowski, II

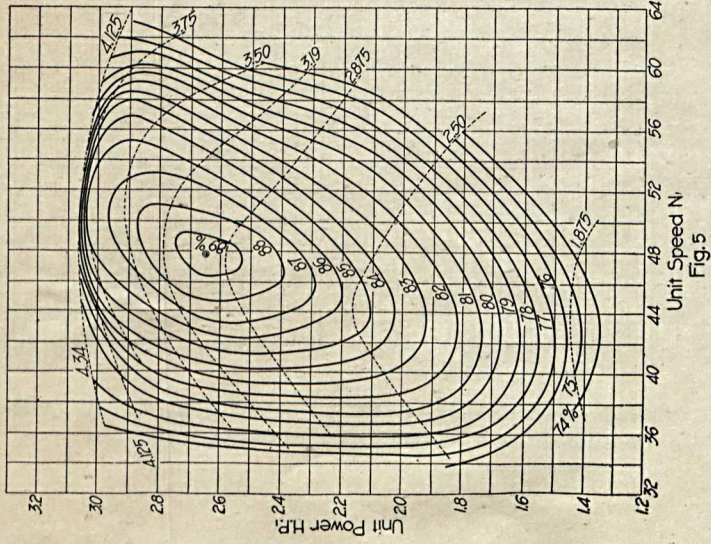


Fig. 5

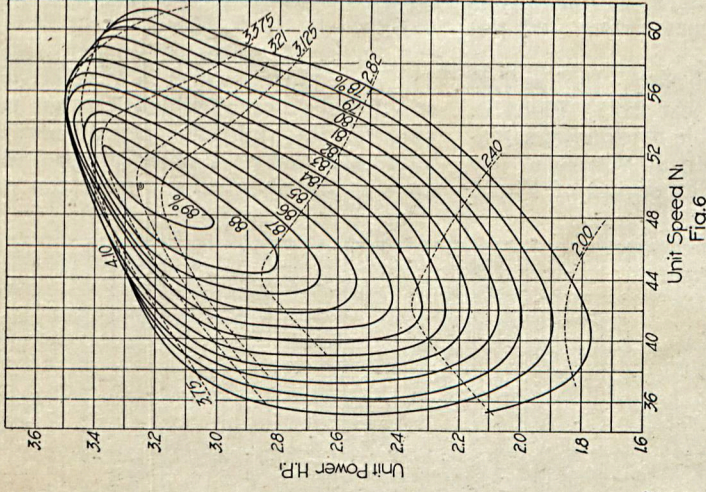


Fig. 6

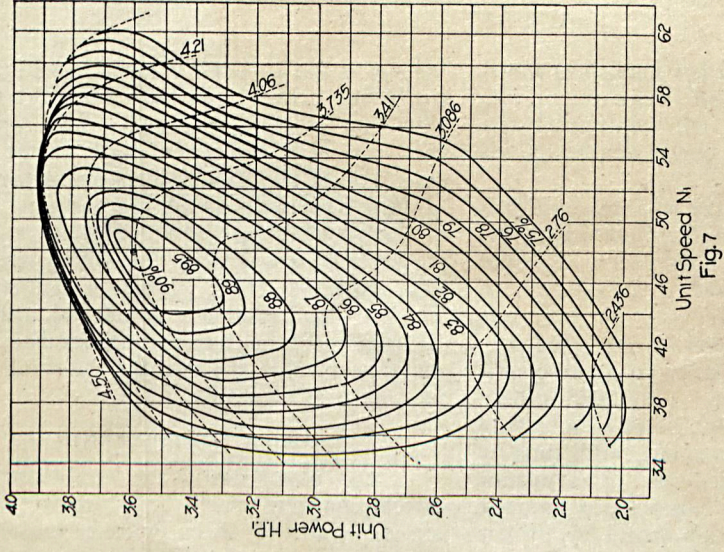


Fig. 7

FIGS. 5-6-7—CHARACTERISTIC CURVES PLOTTED FROM TEST REPORTS OF THE HOLYOKE TESTING FLUME

Test, number	Fig. 5	Fig. 6	Fig. 7
Diameter, inches	2121	2122	2208
Best efficiency, per cent	30	30	30
Normal speed, r.p.m.	89.2	89.3	90.1
Normal power, hp.	48.0	49.9	48.0
Normal K_f (specific speed)	2.65	3.25	3.60
Designer	Zowski, III	Zowski, IV	Zowski, V



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below the normal, for at low heads the wheel must be overspeeded, and if the unit power is then increased this will counteract the reduction of the actual power caused by the decreased head.

Of course, this feature was not obtained without a sacrifice. The best efficiency was reduced, and whether this sacrifice would be too large as compared with the gain to give this turbine a preference over others is a new question, which can be answered only after a thorough investigation of all conditions of the given case. Test 2068 shows, however, the great possibilities of adapting high-capacity wheels to given conditions by using corresponding designs. The author is convinced that it is possible to improve the best efficiency of this wheel by proper design of the runner vanes, without spoiling its particular characteristics just described.

The curves obtained with the second modification (wheel 3, test 2121) given in Fig. 5, show a remarkable broadness, a feature found as a rule only in wheels of low type characteristics. The curves of Fig. 6

belong to the author's wheel 4, a wheel having other proportions than the first three. The best efficiency of this wheel reached the value of 89.3 per cent with a type characteristic of 90. The general characteristics of this wheel are about the same as those of the wheel 1, test 2060. The overload capacity is no worse than that which was usually expected from high-capacity wheels. The part-load efficiency is not bad, although it seems certain that the higher the speed and power value of a turbine the smaller the part-gate efficiency.

OTHER IMPROVEMENTS

In the meantime other engineers were developing new wheels or improving old designs. Two of these wheels interest us here, namely, the I. P. Morris wheel type E, designed by L. F. Moody (test 2026), and the improved wheel of Larner, test 2092. The I. P. Morris wheel is of relatively low-speed and power combination, but remarkable for its high efficiency at normal and part-gate power. Larner's improved wheel gave a higher efficiency than the original

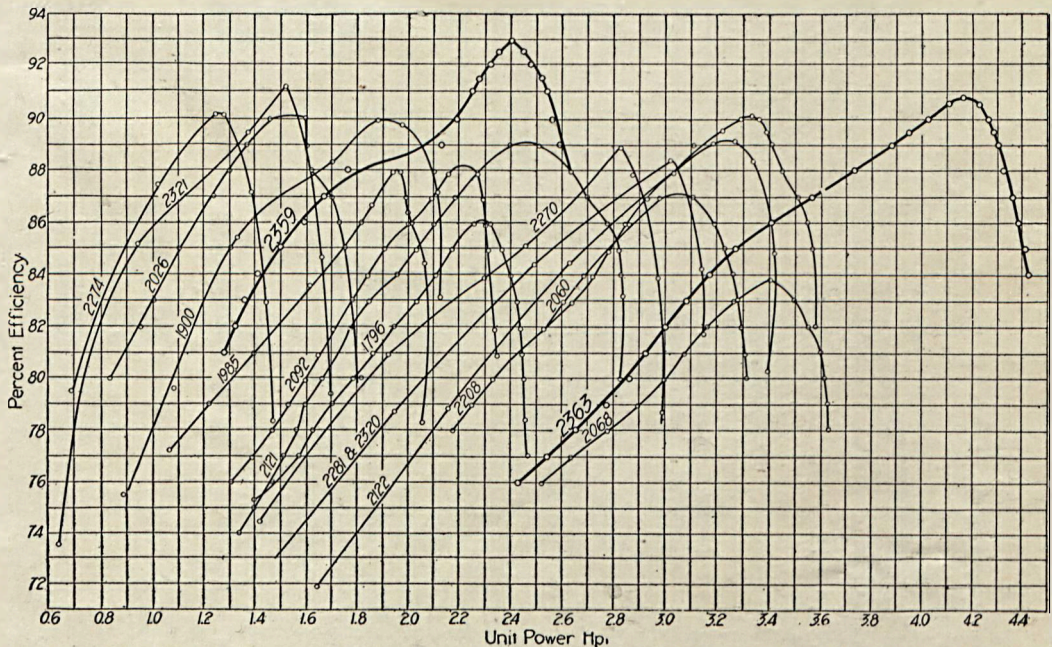


FIG. 8—POWER EFFICIENCY CURVES FOR WHEELS HAVING A NORMAL SPEED OF 50 R.P.M. UNDER A HEAD OF 1 FT.—NORMAL SPEED CURVES

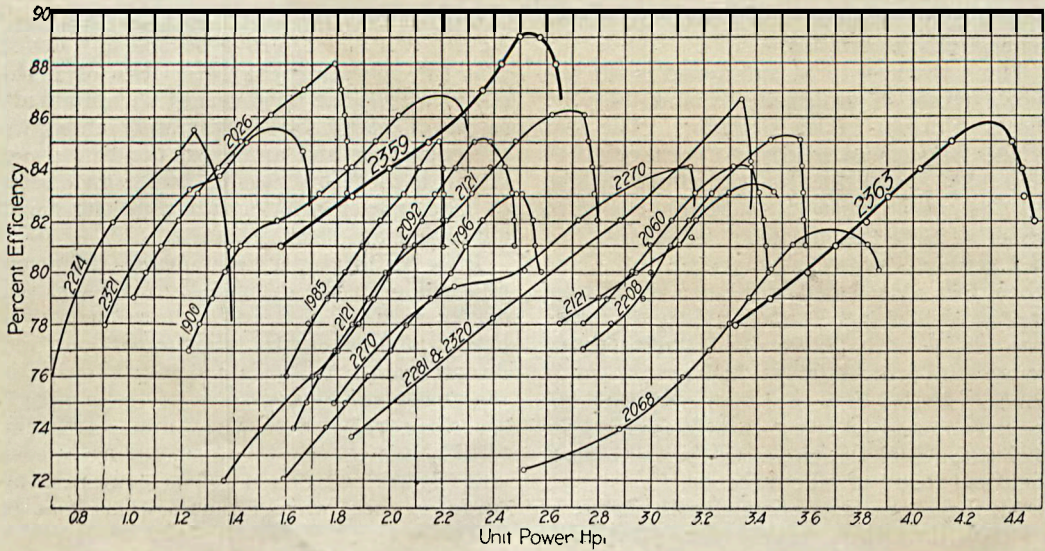


FIG. 9—POWER EFFICIENCY CURVES FOR WHEELS HAVING A NORMAL SPEED OF 50 R.P.M. UNDER A HEAD OF 1 FT.—CURVES FOR 15-PER CENT OVERSPEED

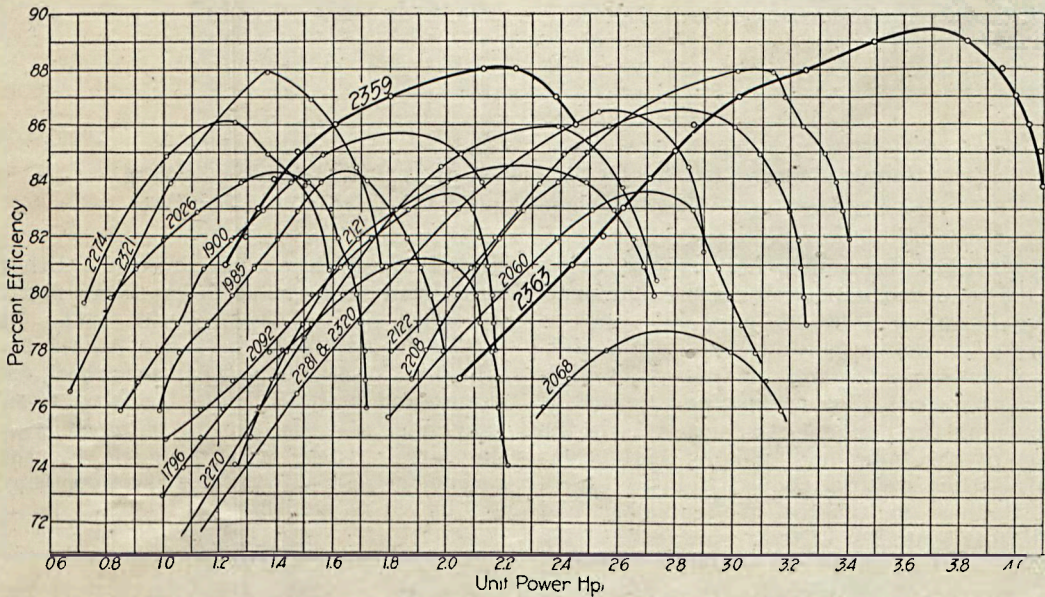


FIG. 10—POWER EFFICIENCY CURVES FOR WHEELS HAVING A NORMAL SPEED OF 50 R.P.M. UNDER A HEAD OF 1 FT.—CURVES FOR 15-PER CENT UNDERSPEED

wheel 1796, maintaining about the same general characteristics.

The last wheel to be mentioned is the author's wheel 5, designed for and built by the S. Morgan Smith Company. The test of this wheel was made in February, 1913 (test 2208), and the result is shown in Fig. 7. The speed-power value is higher than in wheel 4, as is the efficiency, which reached 90.1 per cent (type characteristic 91). This wheel was also tested without a draft tube and gave 86.8 per cent efficiency. It was also tested with sixteen and twelve guide vanes (the original wheel had twenty guide vanes), giving 89.9 and 89.5 per cent respectively, and in every case the same general characteristics appeared in the almost identical shape of all curves.

All the above tests show clearly that it is possible to design wheels for very high speed-power values with good efficiencies and quite satisfactory efficiency curves; that the overload and part-load conditions are not so very bad, although it seems to be true that the higher the type characteristic of the wheel the more difficult it is to obtain very good efficiencies at part load, while it is probably impossible to secure as good values as we can easily obtain with wheels of the lower type characteristics. The tests,

and particularly those of the author's wheels 1, 2 and 3, prove beyond any doubt that the operating characteristics of high-power wheels can be governed within a wide range of possibilities by simply changing the curvature and angles of the vanes and that it is therefore possible to design wheels of high power also to suit conditions and obtain certain desired results.

In order to give a clear idea of the progress made in the designing of wheels, the curves in Figs. 8, 9 and 10 have been prepared. These curves are based on and drawn from the curves as given above, but the power values are, to make the comparison clear, reduced to wheel diameters that would have exactly 50 r.p.m. for their best unit speeds. Fig. 8 shows the load efficiency curves of these wheels when running exactly at best speed, while Figs. 9 and 10 show the same curves when respectively overspeeded and underspeeded 15 per cent.

After this article was written four interesting additional tests of the Wellman-Seaver-Morgan Company were brought to the author's attention. These tests, which are further developments of wheel 1796 and 2092, will be found recorded in the curves of Figs. 8, 9 and 10—tests 2270, 2274, 2281, 2320 and 2321.

Supplementary Article Dealing with Holyoke Test 2359, Giving 93 Per Cent Maximum Efficiency, and 2363, Giving 90.7 Per Cent

WHEN the article bearing the above title and appearing in the Engineering Record of Nov. 28, page 585, went to press the author was studying and analyzing some new reports of noteworthy Holyoke tests, which must now be recorded as marking further important progress in the art of designing and building high-power high-speed water turbines.

During the months of September and October a number of tests were made at the Holyoke testing flume by James Leffel & Company, of Springfield, Ohio. Some of these tests were carried out for purposes of study and were continuations of former

similar systematic experiments. Other tests were made to see what some newly developed turbine types would yield. Of this latter group of tests the results obtained with an improved Samson wheel, designed and built by James Leffel & Company, and also the results obtained with the latest wheel type designed by the author for and built by the same company will be put on record.

TEST 2359

Fig. 11 (continuing the notation in the original article) shows the equal-efficiency curves of the first wheel (Holyoke test

2359). This wheel is a further improvement of the Samson wheel test 1900, the curves of which were given in Fig. 2 of the previous article. The unprecedented efficiency of 93 per cent was realized, with a unit speed of 47.2 r. p. m. and unit power 2.7, as against 90 per cent efficiency with a speed of 45.3 and power of 2.48 obtained with the wheel test 1900. The general good characteristics of operation of the Samson wheel which were pointed out in the original article did not suffer, as is apparent from the broadness of the curves of this new wheel. This wheel now holds the record of the highest efficiency ever obtained in the Holyoke testing flume, and when we consider the speed and power value of the turbine type characteristic $K_t=77.6$ —we must indeed admit that the result is astonishing. The development of the Samson wheels is due to A. F. Sparks, general manager of James Leffel & Company. It was made possible only by going at it in a systematic way, by making ex-

haustive research in the Holyoke flume, which work extended over a period of about twenty years.

TEST 2363

Fig. 12 shows the equal-efficiency curves of a wheel designed by the author for James Leffel & Company. This is test 2363, the author's latest design. The best efficiency reached a value of 90.7 per cent with a type characteristic $K_t=102$, which means a power increase of 25.5 per cent over that of the author's wheel Zowski V, with an efficiency increase of 0.6 points (see Fig. 7 of the first article). The general characteristics of the wheel did not suffer at all, as is apparent from the shape of the curves when

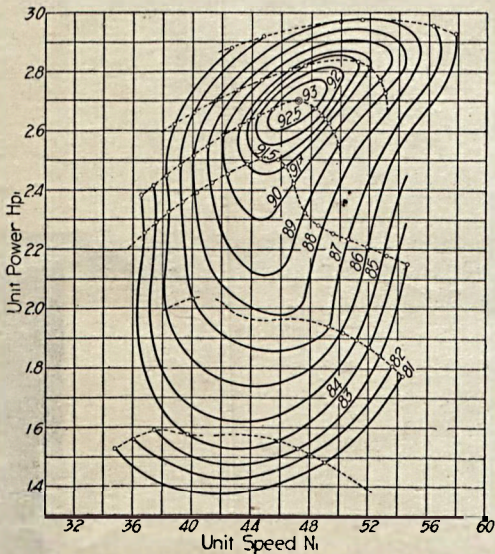


FIG. 11—HOLYOKE TEST RUNNER 2359

Diameter _____ 35 in.
 Best efficiency _____ 93 per cent
 Normal speed _____ 47.2 r.p.m.
 Normal power _____ 2.7 hp
 Normal K_t _____ 77.6 (specific speed)
 Designer _____ A. F. Sparks

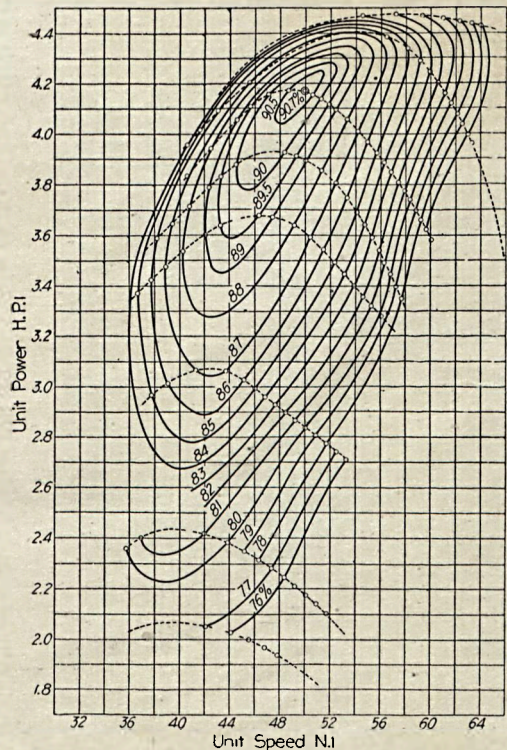


FIG. 12—HOLYOKE TEST RUNNER 2363

Diameter _____ 30 in.
 Best efficiency _____ 90.7 per cent
 Normal speed _____ 50 r.p.m.
 Normal power _____ 4.17 hp
 Normal K_t _____ 102 (specific speed)
 Designer _____ S. J. Zowski

they are compared with the curves shown in Fig. 7 of the original article.

It is interesting to note that both wheels had draft tubes of the same length and the same discharge diameter, making the final discharge loss of turbine 2363 1.1 per cent greater than that of turbine 2359. This means that the rest of the hydraulic losses of turbine 2363 is $93 - (90.7 + 1.1) = 1.2$ per cent higher than for turbine 2359. Considering that turbine 2363 has actually 54 per cent and relatively (that is, when reduced to same speed) 67.1 per cent more power than wheel 2359, the increase of hydraulic loss does not seem to be excessive. From this we might draw the conclusion that if the efficiency of 93 per cent is the highest value we can reach with a wheel having a type characteristic of about 78—and this estimate can not be far from right—then the efficiency of 90.7 per cent must be very near the maximum for a wheel having a type characteristic of about

102. On Figs. 8, 9 and 10 in the first article are shown in heavier lines the power-efficiency curves for the wheels 2359 and 2363.

It must be added and emphasis must be laid on the fact that neither of the turbines should be considered in the light of experimental apparatus, nor should either of the tests be regarded as show tests. The turbines were of commercial design and construction in every respect. The runners were substantially and strongly built, and no modification in the bucket design will be necessary for whatever actual service the turbines will be used or whether they will be of single, twin, triplex or quadruplex type. Similarly the guide case was built in a substantial and commercial manner. The guide vanes were of the regular flutter type, operated by a shifting ring. Their shape and thickness were regular. The workmanship was first class, to be sure, but without exaggeration, such as polished surfaces.

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