ORAL PRESENTATION OF ASME PAPER
"INDEX TESTING OF HYDRAULIC TURBINES"
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Index Testing of Hydraulic Turbines is a means of determining the relative flow through them - as contrasted with the measurement of absolute flow as described in the ASME Power Test Code for Hydraulic Prime Movers.

Those of us who have had personal experience with Index Testing realize its usefulness. However, judging from the relatively small number of units tested by this Method it would appear that the Method has not been adequately publicized.

Our Test Code Committee is presently considering an Addendum to the Code which would recognize Index Testing for certain purposes. However, the need for some publication on the subject appeared to be urgent. It was to fill this immediate need that this paper was undertaken.

Before viewing the lantern slides and going into any of the details of Index Testing it should be of interest to review a little of its history - how it was developed to its present status.

The basic hydraulic principles of Index Testing are not new. Practically all of the Methods of Index Testing are modifications of well known methods of measuring absolute flow.

There are several methods of determining relative flow through a turbine discussed only briefly in the paper. One group of methods, all based on the same principle, has been rather fully described. This group has been, and still is, by far the most commonly used. The Methods in this group are all based on the relation between velocity and pressure in a fluid when flowing through converging and diverging tubes. This relationship was first set forth by the Italian philosopher J. B. Venturi in 1796.

Nearly a century later in 1887, an engineer of the Holyoke Water Power Company, Mr. Clemens Herschal made a very practical application of this relationship and invented the Venturi Meter.

In the first quarter of this century, there was great progress in the turbine industry both as to quality and size of hydraulic turbines. This progress was accompanied by and to a large extent made possible by a corresponding progress in the electrical industry. Thus by the early 1920's all the principal turbine builders had several very large turbines to their credit.

However, the Venturi Meter was not practical for measuring the flow through such huge turbines and other methods were developed as are now described in the Code.

By these methods the absolute flow through the turbine can be measured - at the time the test is run and at the head applying during the test. The data has no application ten years after the test nor to any substantially different head.

Engineers saw - particularly those employed by Power Companies - that it would be of great advantage to know the flow all the time.

Several methods were developed: however, the ones most commonly in use today and which I shall describe briefly, are those developed by Messrs. Winter and Kennedy then of Alabama Power Company and Mr. J. A. Peck then of New England Power Engineering and Service Company.

Both of these methods and many possible modifications of them are based on the Venturi Principle. A differential manometer is connected between two points in the stream flow of the turbine itself - one point being of high pressure and low velocity and the other of lower pressure and higher velocity.

The differential pressure is a measure of the velocity head difference between the two points, the friction loss being negligible.

The manometer differential in feet of water which we shall hereafter call D is

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

The velocity, therefore, $\propto \sqrt{D}$

and $Q = K\sqrt{D}$
which is the basic formula for a Venturi Meter.

In the 1920's in quite a few instances when Acceptance Tests were run, this differential manometer was calibrated against the absolute discharge not only to determine the value of K so that a continuous record of flow would be possible, but also I believe to prove out the method. That is, to show that the discharge did $\propto \sqrt{D}$. It eventually became apparent that Q did $\propto \sqrt{D}$ as long as the piezometers were properly located. It was found that there was considerable latitude in the piezometer location, the essentials being that they were free of eddy effects and that the flow pattern did not change with load at that location. However, by sticking to certain locations and thereby accumulating experience, it was possible to predict the amount of deflection and the value of K in advance, thereby permiting purchase in advance of a continually indicating flow meter.

The experience with these piezometers having been satisfactory, we find starting in the 1930's, these piezometers and differential manometer being used on turbines without any concurrent absolute measurement of discharge at all. When thus used, they indicate only relative flow. Relative efficiency can also be obtained in this way. This is an Index Test in the purest sense.

A series of test runs are made over a range of gate opening. The point where the $\frac{\text{output}}{\sqrt{D}}$ is maximum is the maximum efficiency.

The maximum efficiency can be assumed to be a certain value - say 92%. Then having measured the head and the output accurately, the discharge can be calculated relative to the assumed peak efficiency.

Now, dividing this Q value by $\sqrt{D}$ we have a value of K.

It is not an absolute value - such as would be obtained if we had made an absolute discharge measurement.

It is only as correct as our estimate of the peak efficiency.

By applying this value of K to the $\sqrt{D}$ values at the other gate openings, we can obtain a relative discharge curve and a relative efficiency curve.

The following slides will illustrate

1. Where the piezometers have been located and given satisfactory results.
2. That Index Testing is a dependable and accurate way of determining relative discharge.
3. A general outline of how an Index Test is run.
4. Some of the benefits of Index Testing.
5. Something which does not appear in the preprint of the paper - a list of turbines built by one manufacturer which have been tested by the Index Method.

Slide #1 (Figure 6). This shows the location of the piezometers according to the Winter-Kennedy Method. Usually more than one low pressure tap is installed. The closer (radially) to the stay vanes the greater will be $h_1 - h_2$. By putting in several low pressure taps a choice may be made among them selecting the one which best suits some permanent flow indicating device. From the practical standpoint additional taps add a safety against the possibility of one becoming defective during the test.

Slide #2 (Figure 7). This slide very well confirms the accuracy of index testing by the Winter-Kennedy Method. It is made from the results of the Bonneville Service Unit Test on an 81" adjustable blade turbine. Each point represents an absolute measurement of flow by the salt velocity method and a corresponding manometer deflection. By plotting log D against log Q the points fall very closely on a line such that $Q = KD^{.489}$. A line with exponent .5 would go through the points almost as well. This curve also shows that the relationship holds independently of head - the points being at substantially four different heads. Also the relationship holds independent of quantity of flow - that is the piezometers are not affected by slight changes in direction of flow due to change in gate angle.

Slide #3 (Figure 8). This shows the location of the piezometers according to the Peck Method. Sometimes the high pressure piezometer is placed at an angle clockwise several degrees from that shown.

Slide #4 (Figure 9). A confirmation of the accuracy of the Peck Method is demonstrated here. The test was made on a Francis turbine at the Swinging Bridge Development of Rockland Light and Power Company near Port Jervis, N.Y. The piezometers were located as in the previous slide. The absolute Q measurements were made mostly by salt velocity method but also five points by Pitot Tube. The points fall in line such that the exponent of D is .5 in this case.

Slide #4A - Here is further proof that Q varies as $\sqrt{D}$. This time the absolute water measurements were made by the Gibson Method. This test was made on one of the main Kaplan units at Safe Harbor.

Slide #4B - On the Francis type service units at Safe Harbor, the Differential manometer was calibrated against Current Meter measurements. Here also Q varies as $\sqrt{D}$.

Slide #5 (Figure 10). Sometimes provisions were not made for piezometers and when an Index Test was made it was necessary to install them at the time of the test. These piezometer locations were actually used in such cases. They were only temporary installations for the duration of the test. No absolute Q measurements were made at the time. The purpose of these tests were primarily to determine the best gate-blade relationship on Kaplan Turbines. They served this purpose adequately.

Now we shall run quickly through a series of slides illustrating how an Index Test is run. I have chosen as the example a Kaplan turbine because the benefits of Index Testing are most apparent with this type.

Slide #6 (Figure 11). This is the turbine setting. The piezometer locations were as indicated. The prime purpose of the test was to check the blade-gate relationship. No absolute measurement of the water quantity was made. The manometer was located on the generator floor - this made possible by pressure air on the manometer header.

Slide #7 (Figure 16). This slide shows the objective of the test - When the unit was designed, the relationship marked "Initial Cam" was to the best of anyone's knowledge that which would produce maximum efficiency. Due to differences between the water passages of the model and the prototype, however, actually the best relationship was found on test to be that shown by the curve marked "Optimum Cam". Now let us see how this correct relationship was obtained.

Slide #8 (Figure 12). This is the summary sheet of the actual readings made.

Note 1 - The test was completed in four hours.
2 - We used gross head - it varied little from net.
3 - We measured the generator output, determined the losses and converted to turbine output.
4 - We converted the data to a common gross head of 41 feet. Note that it is $\sqrt{D}$ which varies $\sqrt{H}$ not D.

Slide #9 (Figure 13). $\sqrt{D}$ against servomotor stroke. The points circled through which the dotted lines are drawn are the actual points - plotted as the test was being run. It is best to do this so that any erratic points will show up and can be re-run.

Erratic points might be caused by

1 - Incorrect reading the manometer scale.
2.- Piezometer line not completely bled of air.
3 - Air getting into the turbine from the intake if not sufficiently sealed. (On one occasion on a turbine in a vacuum flume, I found air entering the flume through cracks in the concrete. I got a gallon of roofing compound, a gun caulked the cracks.

Slide #10 (Figure 14). Turbine output versus servomotor stroke at several Fixed Blade Angles.

Slide #11 (Figure 15). Having obtained the basic test data, we now work it into usable shape. First, from the summary sheet we plot HP/$\sqrt{D}$ against Output at the average head during the test.- this series of fixed blade angle curves. Where HP/$\sqrt{D}$ is maximum, is the point of maximum efficiency. In this case 1974 at an output of 6660 HP. We assumed an efficiency of 91% for this point. The turbine was designed for a head of 52 feet. At 41 feet efficiency would be less than normal. Then we can figure Q on this basis. It figures to be 1574 CFS. By referring back to our curves of HP versus gate opening we can determine that at which the output was 6660 HP.

Knowing this gate opening, we can find from the previous curve the corresponding value of $\sqrt{D}$.

It was 3.36

Since $K = \frac{Q}{\sqrt{D}}$, $K = \frac{1974}{3.36} = 467$

Using this K value, the relative discharge at the other points was determined and plotted. The cam was changed to increase the gate opening for a given blade angle. Thus we arrived at our objective - as shown on the cam shape curve which I initially showed you. You can see that an actual gain in efficiency was brought about as result of the test.

Slide #12 (Figure 4). This, together with the next slide, will illustrate an additional use of Index Tests on Kaplan turbines. When a unit is so set with respect to tailwater as to be affected by cavitation, the effects upon power and efficiency may be shown and safe operating limits set. It will be noted that the performance suffers appreciably in both output and efficiency when the blade angle is increased from 28 to 32°. This is the effect of cavitation.

Slide #13 (Figure 5). The heavy full line is the prototype performance determined by an Index Test. The light full line is the model stepped up for size and head when tested in a setting such that cavitation does not occur. The dotted line shows the effect of cavitation on the same model with sigma the same as on the prototype. Note that at 22° B.A.

cavitation had no effect on the prototype or model. At 28°, cavitation did affect the output somewhat, while at 32° the effect is very pronounced. It is obvious that cavitation begins to become serious starting at 28° B.A. and about 70% gate.

Continuing our presentation of the benefits of Index Testing.

Slide #14 (Figure 1) shows a sample of curves whereby for any possible output - either Turbine HP or Generator KW - the operating force knows the gate opening, efficiency and discharge. These curves might be in any or all of several different forms to suit the operating conditions. All against G, O or Q.

Slide #15 (Figure 3). This is an example of periodic Index Testing showing the effects of wear, etc., on the turbine performance. Based on these data an Operating Company may make more intelligent decisions as to the need for reconditioning of the unit.

Slide #16 (Special). This slide shows a list of all the turbines of S. Morgan Smith Company manufacture on which Index Tests have been run. This list was not completed in time to be included in the preprint copies of the paper but will be published with the author's closure. A total of 43 Kaplan turbines and 33* Francis turbines have been Index Tested. This is good, but not good enough - particularly on the Kaplan turbines where the benefits are so worthwhile. The Kaplan units tested represent only about 1/4 of the units of this type furnished by this manufacturer.

In conclusion -

Much useful information can be economically obtained from an Index Test.

Such a test may be conducted in all respects, except for the measurement of the water, in accordance with the ASME Power Test Code. The method is relatively simple and inexpensive.

In a new Kaplan turbine there is no definite assurance that the blade gate relationship is perfect. The odds are great that the turbine would meet its efficiency guarantees with the cam as originally furnished. However, a field test of some kind should be made to make sure that the best possible efficiency is obtained. An Index Test will serve that particular purpose as well as any other kind.

I have personally taken part in many of the Index Tests listed on the last slide and have evidence and know that the Owners and Operators of those units consider carefully conducted Index Tests have provided them with a great deal of essential information with very little expense.

Many more turbine users than have - could profit from Index Testing.

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*This given as fourteen in preprint have since included the early tests where piezometers were calibrated against absolute flow.