Simple Basis for Securing Efficient Hydro Operation

Determination of characteristics of unit performance is necessary in order to make fullest use of available water. Calculation of operating curve does not require complete test of unit, but may be based on the index of one factor.

By F. Nagler
Engineer Hydraulic Department, Allis-Chalmers Manufacturing Company, Milwaukee, Wis.

As the water resources of the country become more and more developed and greater numbers of hydro-electric plants operate on controlled storage it becomes increasingly important in the utilization of investment that every one of these plants shall work as closely as possible to its best point of efficiency. Deviations from this point, except in times of excess water for which no storage is provided, mean actual losses of kilowatt-hours that could have been saved. The quantity of energy lost by inefficient operation may be difficult of exact evaluation, but the loss does exist, and the fact that it is indeterminate should not prevent the effort to save it from being made. To get the most out of a hydro unit a definite operating curve is required. Such a curve is usually considered to be capable of calculation only after extensive tests. Such is not the case, as it is not necessary to make an exhaustive check on a unit in order to erect its operating curve. The curve may be set up on the index furnished by a single and easily secured factor of operation.

In a way all hydro tests are index tests, in that errors or slightly indefinite coefficients such as angular characteristics of current meters, pitot tube coefficients or weir constants are a constant bar to absolute water measurement. The index methods here described simply allow wider latitude in that respect, but in so doing detract in no way from the utility of the resulting operating curve for use in enabling the development of the most kilowatt-hours from available flow. Condition of units may be checked periodically by these methods, but determinations of quantity of water used, absolute efficiencies and comparative performances in respect to other plants may not. The essential features to be watched in making an index test are gate setting, distribution of flow to adjacent units, condition of racks and the use of a single means of measuring output. Gates should always be set by an indicator having the least possible lost motion and always be set in a direction opposite to their drive tendencies.

In this article are given typical examples of operating curves erected on velocity gage, current meter and impact gage tests, together with the mathematics of each case. Whatever manner of test is employed the determination of the curve is based upon the same condition.

Fig. 1—Operating Curve Developed from Velocity Gage Index

This is that the break in the energy output curve of the unit occurs at a gate opening that is at or very close to the most efficient operating point. The other points on the curve are determined in their relations to this one, not necessarily in terms of any test or operating quantities, but only in those relations. That is to say.

November 2, 1929 — Electrical World
the best point at which to operate a unit is at its highest efficiency, but it makes no difference what this point is; the object is merely to establish the curve in relation to it. The break in the output curve is that point where it begins to flatten out, where increases in the gate opening add markedly less to the power output. If the curve has a well-defined "knee" the break is easily and definitely located; if the curve is so smooth as to make the break difficult of exact location the need of its exact location is less important and its reasonable approximation will suffice.

Taken with the foregoing comments, the following examples of typical index test observations, their computations, efficiency assumptions and determinations of operating or index curves should illustrate the limitations and value of this type of test. It should be remembered that for operating purposes the performance curve may be plotted as efficiency, either high or low, or merely as a meaningless number like kw. divided by square root of impact, without detracting from the value of the resulting curve.

**Fig. 2—Operating Curve Developed from Current Meter Index**

The application of a straight velocity gage to the determination of the operating curve of a unit is illustrated in Fig. 1. The plant in question had a single unit of 3,750 hp. at 75-ft. head developed through about 500 ft. of 11-ft. diameter penstock. Two velocity gages were available, one including pipe friction and the other only inlet and rack losses and inlet velocity head. The latter was used. It consisted of two glass tubes connected respectively to the pond and to a flush opening in the penstock about 50 ft. downstream from the racks. The upper ends of each were open to atmosphere and brought adjacent to a common scale on which the difference \( H_v \) was measured. In this type of gage the utmost care is required to keep pipes to the gages free of air. Any connection that will give a readable displacement is satisfactory, whether it arises from friction, velocity or impact. Readable indications may be obtained from low or high pressure effects by using a differential gage based on liquids of densities greater or less than water. The following are commonly available:

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Approximate Specific Gravity</th>
<th>Liquid</th>
<th>Approximate Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>0.7</td>
<td>Carbon tetrachloride</td>
<td>1.4</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.8</td>
<td>Carbon disulfide</td>
<td>1.35</td>
</tr>
<tr>
<td>Water</td>
<td>1.0</td>
<td>Bromoformide</td>
<td>2.9</td>
</tr>
<tr>
<td>Carbon tetrachloride and gasoline</td>
<td>0.7 to 1.3</td>
<td>Mercury</td>
<td>13.0</td>
</tr>
</tbody>
</table>

*Will retain color in presence of water if treated with iodine or some of the aniline dyes.

The data of curves 1 and 2 in Fig. 1 are easily obtained on commercial load and to take them requires only an hour or two for all gates. From this data curve 3 is computed and such a curve is all that is needed for plant operation. The data appear in Table I.

Assuming 80 per cent maximum efficiency (90 or 100 or 60 could be assumed with equal utility) at the "break" of the kilowatt curve, where the best efficiency of a turbine usually occurs and which by inspection is at about 0.7 gate, and as the head in the velocity gage is caused by velocity head and friction head we may fairly assume that it is a function of \( V^2 \) and we may write:

\[ H_v = C \frac{V^2}{2g} \]

or

\[ V = C_1 \sqrt{2gH_v} \]

whence

\[ Q = \frac{AV}{A} = AC_1 \sqrt{2gH_v} \]

For 11-ft. diameter pipe and expressing \( H_v \) in feet in place of the observed inches of water this becomes:

\[ Q = 95 C_1 \sqrt{\frac{2gH_v}{12}} = 220 C_1 \sqrt{H_v} \]

Combined efficiency = \( \frac{kw. \times 1.34 \times 550}{Q \times H_v \times 62.4} \) which, for 75-ft. head and substituting for \( Q \) its value as \( H_v \), becomes

Combined efficiency = \( \frac{kw.}{C_1 \sqrt{H_v} \times 1.397} \) or \( \frac{kw.}{C_1 \sqrt{H_v}} \)

**Table I—Efficiency from Velocity Gage Index**

<table>
<thead>
<tr>
<th>Tenches</th>
<th>Kw.</th>
<th>Output</th>
<th>( H_v )</th>
<th>( H_v ) Assumed</th>
<th>Combined Efficiency</th>
<th>Curve in Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.000</td>
<td>10.00</td>
<td>3.12</td>
<td>3.12</td>
<td>74.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.000</td>
<td>10.00</td>
<td>8.00</td>
<td>2.94</td>
<td>75.0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.000</td>
<td>10.00</td>
<td>3.14</td>
<td>3.14</td>
<td>76.2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4.000</td>
<td>10.00</td>
<td>2.68</td>
<td>2.68</td>
<td>78.0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>5.000</td>
<td>10.00</td>
<td>2.34</td>
<td>2.34</td>
<td>80.0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6.000</td>
<td>10.00</td>
<td>2.03</td>
<td>2.03</td>
<td>82.0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>7.000</td>
<td>10.00</td>
<td>1.67</td>
<td>1.67</td>
<td>84.0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8.000</td>
<td>10.00</td>
<td>1.26</td>
<td>1.26</td>
<td>86.0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>9.000</td>
<td>10.00</td>
<td>0.89</td>
<td>0.89</td>
<td>88.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>10.00</td>
<td>10.00</td>
<td>0.50</td>
<td>0.50</td>
<td>90.0</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>11.00</td>
<td>10.00</td>
<td>0.25</td>
<td>0.25</td>
<td>92.0</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>12.00</td>
<td>10.00</td>
<td>0.05</td>
<td>0.05</td>
<td>94.0</td>
<td></td>
</tr>
</tbody>
</table>

Synchronous condenser operation.
N ow using an assumed 80 per cent efficiency as the test point:

\[ \text{kw.} = \frac{kW}{C_2 \sqrt{H_a}} \]

\[ C_2 = \frac{0.80 \sqrt{H_a}}{\text{kw.}} \]

\[ C_2 = \frac{2,600}{0.80 \sqrt{7.1}} = 1,220 \text{ approximately.} \]

From which the efficiency for all gates may be figured

Combined efficiency = \[ \frac{\text{kw.}}{1,220 \sqrt{H_a}} \]

giving column 3 in Table I. Incidentally, a curve of kw. divided by \( \sqrt{H_a} \) would be as useful for operation, but it is ordinarily desirable to have the curves approximate fairly closely to the absolute efficiency values, which in familiar terms peak between 80 per cent and 90 per cent for combined units.

This particular plant was carefully tested by Professor Allen using the salt titration method. The results are shown in curves 4 and 5. These, of course, give absolute efficiency within the margin of test error and are such that the plant may be used as a check on the river flow and to determine whether the units meet the efficiency guarantees. They do not aid in operation otherwise. The turbine efficiency curve 7 is simply deduced from curves 5 and 6.

These curves of Fig. 1 are representative of the velocity gage type of results. I. A. Winter of the Alabama Power Company has carried this principle one step further by using the variation of pressure from the outside to the inside of a spiral casing near the guide vanes for a source of \( H_a \). This is calibrated by a complete test and a permanent recording meter installed after that calibration to show continuous discharge figures. Caution is required in that connection, not to locate the inner pipe too near the guide vanes as to run into interference that would modify the character of flow past it. E. A. Dow of the New England Power Construction Company has regularly made use of velocity changes in butterfly valves for the same purpose. Such a valve acting exactly like a venturi meter up to the limits of its velocity difference.

Current Meter Index

Exactly comparable results may be obtained in open flume settings by using a current meter or several of them. An index point or a series of them are definitely located and the meter or meters read for five to ten minutes continuously to eliminate pulsating flow effects.

An index reading is thus obtained that is directly proportional to turbine discharge in place of the square root function of the velocity gage. The sketch (Fig. 3), shows a typical power house arrangement in which this form of gage or index test may be used.

Two current meters were fixed at stations 4 and 11 at elevation 3. Adjacent units were operated at fixed gate positions, and the records were kept clean. These precautions are of utmost importance. The data obtained are shown in Table II.

With gate openings, kilowatt loads and velocity indices available the procedure was as follows: From the shape of the kilowatt curves in Fig. 2 seven-tenths gate was assumed to be the best point. Any other gate opening might equally well have been taken without any change in shape of curve resulting.

Combined efficiency = \[ \frac{\text{kw.} \times 1.34 \times 550}{Q \times H \times 62.4} \]

but

\[ Q = C_1 \text{ and } H = 12.6 \text{ it.} \]

So combined efficiency = \[ \frac{\text{kw.} \times 1.34 \times 550}{C_1 \times 12.6 \times 62.4} = \frac{KW}{I \times C_2} = 0.85 \]

Whence \[ C_2 = \frac{100}{0.85 \times 0.85} = \frac{320}{2.15 \times 0.85} = 175 \]

Applying this to the observed index and kilowatt readings, column 3 is obtained. This plots as in curve 3 from the relationship:

Combined efficiency = \[ \frac{\text{kw.}}{I \times 175} \]

The assumption of 85 per cent at 0.7 gate was in error as subsequent test indicated in curve 5. but our curve 3 is as reliable a basis for operating the unit at its best point as is curve 5 and is obtainable with only a fraction of the cost. time and interference with plant operation as is required for a complete test.

Lacking a current meter or a velocity gage an indicating device may be improvised at the plant. A rectangle of two by four's covered with wire netting like chicken wire, or even hoarded up solid if small in area, may be suspended in a flume fixed area.

The more nearly it approaches the area of the flume.