The simulation analysis and operation conditions optimization
of low-head water bulb tubular turbine based on different
guide vane outlet angle

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Abstract. The work of low-head water turbine mainly relies on the large flow rate, but the larger
flow at different positions of the flow channel are easy to cause different hydraulic loss, and they
may also have a poor stability. The paper based on a typical case of low-head water turbine unit
over the Yellow River, according to the efficiency of the low-head water turbine and the hydraulic
loss theory, and according to the real machine guide vane and the surface shape of turbine vane,
and when a fixed vane turning, change the guide vane outlet angle and calculate the computing
velocity and energy characteristics, then the unit was found with the highest efficiency between
the 200 m³/s - 250 m³/s , and then we put forward the concept of conditions interval
optimization from the angle of theory. Do corresponding numerical simulation on its working
conditions and the real machine test under the same working condition, the test results consistent
with theoretical calculation. In combination with theoretical calculation and the real machine test
conclusion, and on the basis of the conclusion of low-head water turbine to make condition
optimization and through the actual operation to achieve a certain effect, which provide a
solution for the economical and safe operation of the low-head water turbine.

1. Introduction
In China, from the investment point of view, hydropower investment has gradually exceeded the thermal
power investment. From the installed capacity point of view, in 2014, the hydropower installed capacity
made a historic breakthrough of 300 million kilowatts and the hydroelectric power generation is a
historical breakthrough of 1 trillion KWH, water and electricity continues to be the main force of energy
conservation and emissions reduction. And the low - head hydraulic energy machinery is an important
part of the national power grid, the model is also the country's active promotion of green energy
equipment, but often because of the bigger waterhead change rate of the low-head water turbine, which
is easy to cause larger hydraulic loss and has a poor stability phenomenon [1-3]. The Yellow River estuary
Hydropower Station, the designed water head is 5.8 m, installing 4 low-head water turbine units of 18.5
MW, the hydraulic loss under different cases was 15%. Xiaohezi Hydropower Station and Jin Gou power
station are of low-head water turbine, the hydraulic loss were all higher than 12%. So it is particularly
important to research the condition optimization of the low-head water turbine. There are few researches
on the optimization of the operating conditions of low -head water turbine in the academic field, in the
literature [4-6], only the turbine association league condition were studied. Literature [7,9] is a theoretical analysis of efficiency. The flow field and stability of small turbine are studied by [10-12].

The paper first made a calculation and analysis from the hydraulic theory, numerical simulation and field test were taken in the same condition of turbine, study the working condition optimization of low-head water turbine, which provide a solution for the economic and safe operation of the low-head water turbine.

2. Hydraulic loss and the parameters theoretical analysis

In general, when the unit velocity keeps unchanged, with the change of the low-head water turbine guide vane outlet angle, the change rule of each part's hydraulic loss in the flow channel [13];

\[
\frac{d\xi}{da} = \left(\frac{Q_i}{\sin \beta_{in}}\right) \frac{df_i(C_r)}{df_i(C_r)} + \frac{1}{(\cot a + \cot \beta_0)\sin^2 a} + 2f_i(C_r)(\cot a + \cot \beta_0)\sin a^2 a_i + 3f_i(C_r)(\cot \beta_i)\sin a^2 a_i
\]

in the formula

\[
f_i(C_r) = \frac{D_kK}{2g}
\]

\(\xi\) low-head water turbine wing type resistance loss and end loss relative coefficient, \(Q_{in}\) is the unit flow, m³/s; \(a_i\) is guide vane outlet angle. \(\beta_{in}\) is the relative inlet angle; \(\beta_0\) is the turn angle of the runner vane; \(D_k\) is the cascade resistance coefficient; \(k\) is the influence factor of the runner, \(g\) is the gravity acceleration, m/s².

By analyze formula (1), we got \(d\xi/da_i>0\), so when the runner keep a certain unit of velocity and vane angle, the sum of the wing type loss and end loss increases with the inlet angle (guide vane opening).

\[
\frac{d\xi}{da_i} = (\cot \beta_i - \cot \beta_{in}) \frac{2KQ_{in}^2}{[4(1 - d^2)]^{1+\tau} 30\eta_n g \pi F_{in}} + \frac{Q_{in}^2}{(\cot a_i + \cot \beta_0)\sin^2 a_i\sin \beta_i} + \frac{1}{(\cot a_i + \cot \beta_0)\sin^2 a_i}
\]

In which, the \(\xi\) is turbine vanes inlet impact loss coefficient.

By analyze formula (2), when \(d\xi/da_i=0, \beta_i=\beta_{in}\), there is no impact inlet and the loss is the minimum, then there is the optimal unit parameters \(a_{i10}, Q_{in10}\), when \(a_i > a_{i10}\) and \(Q_{in}\) increase, \(\cot \beta_i\) increased, then \(d\xi/da_i<0\), which form a negative angle of attack and produce the impact on the back of the guide vane; When \(a_i < a_{i10}\), with the increase of \(Q_{in}\), thus \(d\xi/da_i>0\), which form the positive attacking angle and produce impact on the front of the guide vane.

The change of inlet and outlet velocity of water turbine runner is the key parameter that affects the energy characteristic of water turbine. Theoretically analyze, when \(\beta_i = \beta_{in}\), the impact loss changed to positive impact characteristics and negative impact characteristics, which has a larger influence on the energy loss and stability of water turbine. The calculated object are as follow: water head is 5.8 m, nominal rating 18.5 MW, rated velocity 68.18 r/min, and assume that the water turbine vane angle was laid for 31 °, the guide vane opening ° changes from 53.9 to 53.9 °, the changes of the outlet velocity
Figure 1. Vane 31° guide vane 53.9° ~ 58.8° the velocity triangle of the runner inlet and outlet

The water turbine's water head is 5.8 m, when the vane was laid at a angle of 31°, the guide vane angle changed from 53.9° to 58.8°. As can be seen from the figure 1, the circumferential velocity \( \mathbf{u}_1 \) \( \mathbf{u}_2 \) keep unchanged, however the inlet, relative velocity \( \mathbf{\omega}_1 \) \( \mathbf{\omega}_2 \), gradually increase, absolute velocity \( \mathbf{v}_1 \) is also gradually increase, according to the water turbine static state torque equation to get the input energy increases gradually, at the guide vane angle of 53.9°, 56.6° and 58.8°, these 3 working conditions, the inlet from positive impact to no impact and then to the negative impact. The guide vane angle of 56.6° is an optimal optimization condition.

3. The Simulation Calculation Analysis
This paper selected a typical low-head water turbine over the Yellow River as the simulation object. As shown in figure 2, it is a full flow channel entity model, which was constituted by water turbine inlet port, runner part and tail water part, 16 guide vanes, 4 vanes, inlet and tail water tube adopted the structured grid and the guide vanes and the runner vanes used unstructured grid, which were shown in table 1. Take the RNG \( k-\omega \) turbulence model, inlet mass flow and given the outlet according to the static pressure, the residual value is \( 1 \times 10^{-4} \).

| name          | node  | elements |
|---------------|-------|----------|
| Guide leaf    | 1241343 | 6013545  |
| blade         | 344167  | 1826431  |

Figure 2. Full passage of the mesh distribution
When the water head is 5.8 m, the water turbine vane angle was laid at 31 °. The calculation set up three working conditions, as shown in table 2, the guide vane increased from 53.9 ° to 53.9 °, the output power of the water turbine increased by 0.45 MW, the water turbine efficiency increased from 92.79% to 93.04%, when reduced to 92.74%, that is to say, the water turbine's settling angle is 31 °, by changing the way of guide vane, the energy characteristics first increased and then decreased, this characteristic is exactly the same as that of hydraulic loss and the parameters theoretical analysis.

| guide vane opening(°) | 53.9 | 56.6 | 58.8 |
|-----------------------|------|------|------|
| output(MW)            | 8.65 | 9.01 | 9.10 |
| effectiveness(%)      | 92.79| 93.04| 92.74|
| flow(m³/s)             | 117.20 | 120.84 | 122.89 |

In figure 3, A, B and C are respectively for the three working conditions internal vorticity distribution map of 5.8 m water head turbine and the laid angle of 31 °, which with the guide vane opening change from 53.9 ° to 58.8 °. Under the three conditions, there is a more obvious vortex vorticity in the tail water tube. In the 53.9° mode, there is a certain amount of vorticity and there is a certain energy dissipation at the tail water tube, the tail water energy recovery is good. In 56.6° mode, vortex number added and the energy dissipation of tail water increased, which has the highest energy recovery; In 58.8° mode, the vortex number decreased.

Figure 3. 31° blade when conditions change vorticity

As can be seen from the above, in figure A to C, the efficiency of A and C are lower, mainly the role of energy recovery of the tail water tube, the abnormal outlet lead the flow field more complex. In the optimal condition of area B, there is no impact inlet and keep a high efficiency and the normal outlet flow field is relatively stable, which is consistent with the runner hydraulic loss analysis.

4. Test and Working Condition Optimization
The test object is selected as the same object as the simulation model, to take the real machine test with the water head of 5.8 m and water turbine vane laid angle of 31 ° and the experiments start from the three working conditions of guide vane from 53.9 ° to 58.8 °, and compared with the results of numerical calculation. Test method is the relative efficiency of the index method, test instruments and measuring methods used are shown in table 3. By measuring the flow channel pressure difference to calculate the index flow and then to replace the real flow, and the other main parameters take automatic acquisition and processing by "hydro-set efficiency testing system", finally calculate the water turbine relative
efficiency and output power, set the optimal efficiency point.

Data in table 4 shown that, from the aspects of energy, at the same working condition, the efficiency of low-head water turbine has the same trend, output power deviation less than 2%, thus we can think real machine simulation results are in agreement with the test results. The theoretical analysis and numerical simulation of hydraulic losses are correct, the optimal condition of optimization can be obtained from the method of theoretical analysis and numerical calculation.

**Table 3. The required test equipment and measurement methods**

| serial number | measured parameters | symbol | meter | range | accuracy | measurement methods |
|---------------|---------------------|--------|-------|-------|----------|---------------------|
| 1             | guide vane opening  | α      | governor opening indicator | /     | ±1%      | read                |
| 2             | paddle opening      | Φ      | governor opening indicator | /     | ±1%      | read                |
| 3             | upstream and downstream water level | Z_α, Z_β | water level gauge | /     | ±1%      | check after reading |
| 4             | generator active    | N_r    | power transmitter         | 866W  | 0.2      | computer acquisition|
| 5             | generator reactive power | N_w   | power transmitter         | 866Var| 0.2      | computer acquisition|
| 6             | flow inlet pressure | P_1    | pressure Transmitters     | 300kPa| 0.2      | computer acquisition|
| 7             | flow differential pressure | √h   | pressure Transmitters     | 25kPa | 0.2      | computer acquisition|
| 8             | tail pipe outlet pressure | P_2  | pressure Transmitters     | 250kPa| 0.2      | computer acquisition|
| 9             | wave                | f      | frequency transmitter     | 45--55Hz| 0.5     | computer acquisition|
| 10            | power factor        | COSφ   | power transmitter         | /     | 0.25     | calculation         |

**Table 4. 5.8m working head at Real Test Data Comparison and Simulation**

| condition | guide vane angle (°) | test head (m) | test output (MW) | test efficiency (%) | calculate the head (m) | Calculate the force (MW) | Computational efficiency (%) |
|-----------|----------------------|---------------|------------------|---------------------|-----------------------|--------------------------|-----------------------------|
| 1         | 53.9                 | 5.81          | 6.81             | 94.87               | 5.8                   | 8.65                     | 92.79                       |
| 2         | 56.6                 | 5.97          | 7.20             | 95.06               | 5.81                  | 9.01                     | 93.04                       |
| 3         | 58.8                 | 5.8           | 7.26             | 94.98               | 5.00                  | 9.10                     | 92.74                       |

For low-head water turbine working conditions optimization, which is based on the theoretical analysis and by numerical simulation method to design the optimal operating working conditions area and such as shown in figure 4, we got that the unit has the optimal operation area between 200 m³ / s and 250 m³ / s. By shown in table 6, after a long period of operation, the water turbine's efficiency is increased by 2 to 8%. At the tail water part of the unit installed special pressure sensor (Swiss KELLER, accuracy of ±0.2%) , by measuring, we can collect the pressure pulsation of the tail water tube. Compared figure 5 and figure 6, at the runtime, the pressure pulsation change of the tail water tube in the area is stable and in the optimal operation area, the pulsation is reduced, which is basically consistent with theoretical analysis [13, 14].
Figure 4. Full conditions optimal operating region

Figure 5. Non-optimal operating zone pressure pulsation

Figure 6. Optimal conditions zone pressure pulsation
Table 5. Compare actual operating data

| condition | guide vane opening (%) | Guide vane angle ('') | Test head (m) | Test output (MW) | Test relative efficiency (%) | Design head (m) | Design output (MW) | Design relative efficiency (%) | Design flow (kg/s) |
|-----------|------------------------|-----------------------|---------------|-----------------|---------------------------|----------------|-------------------|-------------------------------|------------------|
| 1         | 76.1                   | 53.56956              | 7.02          | 16.83           | 93.49                     | 7.04737        | 16.9626           | 96.6235                       | 215876           |
| 2         | 77.9                   | 54.0998               | 7.03          | 17.38           | 95.46                     | 7.03057        | 17.5772           | 96.1896                       | 225764           |
| 3         | 79.5                   | 55.4692               | 7.00          | 17.79           | 96.17                     | 7.0103         | 17.8777           | 96.7643                       | 229769           |
| 4         | 81.3                   | 56.8843               | 6.99          | 18.07           | 96.89                     | 7.01711        | 18.2719           | 96.6275                       | 232946           |
| 5         | 83.4                   | 57.6761               | 7.01          | 18.29           | 96.51                     | 7.01661        | 18.4448           | 96.5089                       | 238009           |
| 6         | 85.5                   | 58.2589               | 6.97          | 18.34           | 95.27                     | 7.01469        | 18.4677           | 96.2492                       | 245786           |

5. Conclusion

The paper based on the study of the inlet water flow angle of the runner, a theoretical method for determining the optimal operation area of the tubular turbine was obtained.

Through the analysis of the fixed - our numerical calculation results of 31 ° with different guide vane opening as well as the water turbine internal vorticity distribution map, we can conclude that when the guide vane opening at the angle of 56.6 °, there is no impact inlet, the efficiency is high and the flow field is relatively stable, which is the optimal condition area.

Based on the calculation and analysis of hydraulic theory to take numerical simulation and the real machine test in the same working conditions of water turbine and research the working condition optimization of the low-head water turbine, we got the conclusion that when the unit's optimal operation area is between the 200 m³/s and 250 m³/s, and this conclusion has been proved by the practice of a long-term operation.

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