Numerical Calculation and Analysis of Hydraulics about Inlet/Outlet Based on CFD

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Abstract: Pumped storage power station inlet/outlet is two-way flow, the reservoir water level changes frequently during the operation of the power station. Hydraulic conditions in inlet/outlet area are complex. Inflow conditions are prone to inhalation vortices at low water levels. Outflow conditions are prone to reverse negative flow velocity, which can cause the trash rack to oscillate. Therefore, it is very important to design the the type of build inlet and outlet properly.

1. Introduction

Pumped storage power station inlet/outlet is two-way flow, the reservoir water level changes frequently during the operation of the power station. Therefore, it is very important to design the type of build inlet and outlet properly [1]. If there is an open channel at the inlet/outlet of the reservoir, then the open channel section should meet: (1) The water flow in the open diversion channel is good and the water surface fluctuation is weak. (2) The bottom of the canal and the shore are not washed and the surface eddy current strength is low or there is no eddy current.

The inlet/outlet of the pumped-storage power station has two operating conditions, which are power generation and pumping and the direction of water flow is opposite. Entering flow need prevent the inhalation vortex and outflow need make the water flow evenly spread. At the same time, the head loss of the two operating conditions is required to be as small as possible. With reference to the construction experience of pumped-storage power stations at home and abroad, the following control principles are proposed for the inlet/outlet size:

1. The average flow velocity at the inlet/outlet trash rack is controlled at 0.8m/s~1.0m/s.
2. When inflow, no harmful vortex motion is generated, especially inhalation vortex.
3. When outflow, the flow distribution between the holes is reasonable and the flow difference between the holes is not more than 10%. The water flow spreads evenly. The unevenness coefficient of the flow velocity of each hole should be less than 2, preferably less than 1.6 and no reverse flow velocity is generated, so as to avoid vibration and damage of the trash rack.
4. The water flow in the open diversion channel is good and the water surface fluctuation is weak. The bottom of the canal and the shore are not washed and the surface eddy current strength is low or there is no eddy current.
2. Establishment of calculation model

2.1. Numerical solution method
This study uses a $k-\varepsilon$ mathematical model of turbulence. The specific expression is as follows:

$$\frac{\partial p}{\partial t} + \frac{\partial p u_i}{\partial x_i} = 0$$

(1)

$$\frac{\partial p u_i}{\partial t} + \frac{\partial p u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu + \mu_t\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

(2)

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\mu + \mu_t\right)\frac{\partial k}{\partial x_j} + G - \rho \varepsilon$$

(3)

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\mu + \mu_t\right)\frac{\partial \varepsilon}{\partial x_j} + C_{\mu} \frac{\varepsilon}{k} G - C_{\mu} \varepsilon$$

(4)

$$\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}$$

(5)

$$G = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

(6)

2.2. Model building and meshing
Upper reservoir single inlet/outlet numerical calculation reservoir simulation range is 171×113m (length×width) and simulated length of downstream tunnel is 100m. When generating electricity, the 2 flow passages of the upper storage inlet/outlet are numbered 1# ~2# flow passages from left to right along the flow direction. The section of the reservoir is given the corresponding reservoir water level and the section of the tunnel is determined by the flow rate in a steady state [2].

![Figure 1 Geometric model of inlet/outlet](image1)
![Figure 2 Partial grid division of inlet/outlet](image2)

3. Model calculation
There are many working conditions in this calculation and there are many changes in the calculated water level. This calculation example only shows the case of simultaneous pumping and power generation at the water inlet/outlet in the case of dead water level [3].

3.1. Control section layout
According to the needs of the research content, the data monitoring section is arranged as follows:

Vertical water flow direction cross section: (1) Section 1-1 is at 50m before the intake/outlet. (2) Section 2-2 is at 20m. (3) Section 3-3 is at the rear edge of the trash rack. (4) Section 4-4 is at the end of the diffusion section.

Longitudinal section in the downstream direction: (1) One longitudinal section is arranged along the center line of inlet/outlet of 1# and 2#. (2) Horizontal sections are arranged at different elevations. Horizontal sections z636.8 and z640.8 are arranged at elevations of 636.80m and 640.80m.
3.2. Power generation conditions

3.2.1. Flow regime (streamline and velocity cloud diagram)
The cloud diagrams of the velocity distribution of each horizontal section and vertical section are shown in Figures 4~7. It can be seen from the distribution of the velocity cloud map and the distribution of streamlines. In power generation conditions, inlet/outlet flow lines are smooth. Water flow can flow smoothly from around the reservoir to the inlet/outlet. No vortex is found near the water inlet/outlet. The flow lines in the reservoir are evenly distributed. There is no backflow zone and the flow pattern is good.

3.2.2. Flow velocity distribution
Under the operating conditions of dual generators, the water flow is in good condition. The average
velocity and maximum velocity distribution of each section are shown in Table 1. The flow velocity in
the reservoir area is less than 0.20m/s, so there will be no erosion. The average flow velocity of the
trash rack cross-section is 0.792m/s, which meets the specification requirements. The flow velocity is
the largest at the end of the diffusion section in the flow channel, which is 4.065m/s.

Table 1 Average velocity distribution of each cross section

| Section | 1-1  | 2-2  | 3-3  | 4-4  |
|---------|------|------|------|------|
| Average velocity (m/s) | 0.159 | 0.193 | 0.792 | 4.065 |

The average velocity of the section of the trash rack is less than 1.0m/s, which meets the the
specification requirements. The coefficient of uneven flow velocity distribution during dual generator
power generation is 1.12~1.32, which meets the the specification requirements [4].

Table 2 Uneven coefficient of flow velocity of trash rack trough
under dead water level dual power generation conditions

| Duplex operation | Inlet/Outlet Orifice Number | Maximum flow rate (m/s) | Average velocity (m/s) | Non-uniformity coefficient |
|------------------|---------------------------|-------------------------|------------------------|---------------------------|
| 1# inlet and outlet | a  | 0.814 | 0.725 | 1.12 |
|                   | b  | 0.835 | 0.671 | 1.24 |
|                   | c  | 0.909 | 0.697 | 1.30 |
| 2# inlet and outlet | a  | 0.915 | 0.783 | 1.17 |
|                   | b  | 0.843 | 0.64  | 1.32 |
|                   | c  | 0.95  | 0.774 | 1.23 |

Note: a, b, c select the vertical line of the middle point of the flow channel at the side hole, middle hole and side
hole trash rack; use the five-point method (top, 0.2h, 0.6h, 0.8h, bottom) to determine the maximum speed and
average speed.

3.2.3. Flow distribution
The calculation results of the flow distribution of each inlet/outlet are listed in Table 3. Under this
working condition, the side hole flow is slightly larger and the middle hole flow is small. The split
ratio of each flow channel is between 31% and 35%. The flow distribution is more uniform. The shunt
coefficient is between 0.94 and 1.04, which meets the requirements of the specification. Indicating that
the inlet/outlet flow distribution is balanced and the body shape design is reasonable. The flow
difference is less than 10%.

Table 3 The flow distribution coefficient of the inlet/outlet orifice
of the dual-engine power generation at the dead water level

| Duplex operation | Total flow (m³/s) | Inlet/Outlet | flow (m³/s) | Split ratio | Shunt coefficient |
|------------------|------------------|--------------|-------------|-------------|------------------|
| 1# inlet and outlet | 168              | a            | 57.65       | 34%         | 1.03             |
|                   |                  | b            | 52.97       | 32%         | 0.95             |
|                   |                  | c            | 56.93       | 34%         | 1.02             |
| 2# inlet and outlet | 168              | a            | 57.34       | 34%         | 1.02             |
|                   |                  | b            | 52.66       | 31%         | 0.94             |
|                   |                  | c            | 58.00       | 35%         | 1.04             |
3.3. Pumping conditions

3.3.1. Flow pattern (streamline and velocity cloud diagram)

The inlet/outlet of the upper is outflow. The cloud diagrams of the velocity distribution of each horizontal section and vertical section are shown in Figures 8-11. It can be seen from the distribution of velocity clouds and the distribution of streamlines, the mainstream of the right orifice of 1# inlet/outlet and the left orifice of 2# inlet/outlet is close to the middle and upper part, and the mainstream of other orifices is close to the middle and lower part. The main water flow at the right orifice of 1# inlet/outlet and the left orifice of 2# inlet/outlet does not spread in a straight line in the reservoir area. The other orifices correspond to the reservoir area water flow close to the bottom riverbed. The mainstream flow velocity is about 1.0m, which will not cause riverbed erosion.

![Figure 8 Streamline distribution in the upper reservoir](image1)

![Figure 9 Streamline and velocity distribution cloud diagram on the horizontal plane (z=638.8m)](image2)

![Figure 10 Vertical section a-a velocity cloud diagram and streamline (1# inlet/outlet)](image3)

![Figure 11 Vertical section b-b velocity cloud diagram and streamline (2# inlet/outlet)](image4)

3.3.2. Flow velocity distribution

Under dead water level and pumping conditions, the average velocity distribution of each section is shown in Table 4. The reservoir area has a low flow velocity and will not scour. The average flow velocity of the trash rack cross-section is 0.834m/s, which meets the requirements of the specification. The flow velocity at the end of the diffusion section in the flow channel is the largest.
Table 4 Average velocity distribution of each cross section

| Section | 1-1  | 2-2  | 3-3  | 4-4  |
|---------|------|------|------|------|
| Average velocity (m/s) | 0.401 | 0.401 | 0.834 | 3.56 |

Under pumping conditions, the water flows out from the inlet/outlet. The average flow velocity of the trash rack section is less than 1.0m/s and the uneven velocity distribution coefficient is between 1.71 m/s -1.89 m/s. The flow velocity distribution still can meet the specification requirements.

Table 5 Uneven coefficient of flow velocity of trash rack trough under dead water level pumping conditions

| Duplex operation | Inlet/Outlet Orifice Number | Maximum flow rate (m/s) | Average velocity (m/s) | Non-uniformity coefficient |
|------------------|-----------------------------|-------------------------|------------------------|---------------------------|
| 1# inlet and outlet | a                           | 1.253                   | 0.73                   | 1.71                       |
|                   | b                           | 1.246                   | 0.66                   | 1.89                       |
|                   | c                           | 1.236                   | 0.70                   | 1.77                       |
| 2# inlet and outlet | a                           | 1.278                   | 0.75                   | 1.71                       |
|                   | b                           | 1.159                   | 0.66                   | 1.75                       |
|                   | c                           | 1.182                   | 0.67                   | 1.75                       |

Note: a, b, c select the vertical line of the middle point of the flow channel at the side hole, middle hole and side hole trash rack; use the five-point method (top, 0.2h, 0.6h, 0.8h, bottom) to determine the maximum speed and average speed.

3.3.3. Flow distribution

The calculation results of the flow distribution of each inlet/outlet are listed in Table 6. 1# inlet/outlet diversion ratios are between 32%~35% and diversion coefficients are between 0.95~1.05. 2# inlet/outlet diversion ratios are both between 32%~36% and diversion coefficients are between 0.95~1.08. The flow is evenly distributed, which indicates that the inlet/outlet body design is reasonable.

Table 6 The flow distribution coefficient of the inlet/outlet orifice of the pumping generation at the dead water level

| Duplex operation | Total flow (m³/s) | Inlet/Outlet | flow (m³/s) | Split ratio | Shunt coefficient |
|------------------|------------------|--------------|-------------|-------------|------------------|
| 1# inlet and outlet | 151             | a            | 52.93       | 35%         | 1.05             |
|                   |                  | b            | 47.81       | 32%         | 0.95             |
|                   |                  | c            | 50.61       | 33%         | 1.00             |
| 2# inlet and outlet | 151             | a            | 54.2        | 36%         | 1.08             |
|                   |                  | b            | 48.02       | 32%         | 0.95             |
|                   |                  | c            | 48.80       | 32%         | 0.97             |

4. Conclusion:

(1) Under power generation conditions, the flow rate and flow distribution of the inlet/outlet is reasonable and meets the requirements of the specification. No vortex is found near the inlet/outlet and the flow pattern is good.

(2) Under pumping conditions, the flow velocity distribution of the trash rack section and the flow distribution of each orifice meet the requirements of the specification. The flow in the reservoir area is asymmetrical and the flow pattern is difficult to achieve uniformity.

(3) The flow spreads slowly in the reservoir area and tends to the left bank. The main flow velocity of the water in the reservoir area is basically about 1.0m/s under various conditions. The average
velocity is 0.5m/s, which will not cause erosion and can meet the specification requirements.

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