Optimal design of a pelton turbine nozzle via 3D numerical simulation

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Abstract: Currently, untapped water resources in China are mostly located in the southwestern region notable for high ranges of Qingha-Tibet Plateau, Hengduan Mountains and Yunnan-Kweichow Plateau. These water resources have the remarkable property of being high in water head within a short distance. The Pelton turbine counts as the most adequate type of water turbine to harness these water resources. An internal-controlled Pelton nozzle design is elucidated in this paper in line with the formula and an existing model in the case of 1100m water head [1]. The impact exerted by nozzle and spear angle on the nozzle hydraulic efficiency under a set of needle strokes was ascertained from the numerical perspective. Elucidated hydraulic performance of different nozzle design was anatomized. An energy criterion was proposed through acquiring the jet efficiency to select the appropriate hydraulic design of Pelton nozzle [2]. The numerical results were indicative of the design with 100°/70° combination of nozzle and spear angle that was superior in overall hydraulic efficiency. For this reason, this design can be referenced in engineering applications.

1. Introduction
China's river water resources are notable for their high gaps and steepness. On the "roof of the world", numerous great rivers, inclusive of the Yangtze River, the Yellow River, Nu River, Lancang River and Yarlung Zangbo River, originated overall from the Qinghai Tibet Plateau, have a natural water flow gap up to approximately 5000m. These water resources with high water head have great potential. Accordingly, these shall be adequately harnessed.

When selecting a proper approach to harness these high-head water resources, the reaction turbine is evidently disadvantaged in many aspects, inclusive of a large amount of excavation, serious cavitation and its low adaptability in the case of large-load fluctuation [3-7], whereas the impulse turbine can be ideally geared into the variations with high head and large load. In the case of this circumstance, the kinetic energy of the water flow can be adequately harnessed. As a result, the research and development of high-head impulse water turbine shall naturally become the trend of water resources harnessing and development in China.
The Pelton turbine has been described clearly in internal pressure distribution, dynamic characteristics [8-14]. Therefore, the design and optimization have good prospects for research [15]. The injection mechanism of Pelton turbine first transports the water flow to high-speed jet, inject it into the atmosphere and let it hit the surface of the runner. The injection mechanism is attached the critical significance to in the form of energy conversion. Accordingly, the injection efficiency of the injection mechanism exerts a significant impact on the efficiency of the whole bucket type turbine.

2. Simulation model

2.1. Geometry of the model
The nozzle structure denotes a curved surface smoothly connected with the straight pipe section in the front, and the needle tip refers to a conical structure smoothly connected with the curved surface in front of the tip. The dimension of the nozzle structure primarily comprises: nozzle diameter $D_0=240$mm, nozzle length $L=10D_0$ and nozzle inlet diameter $D=1.19D_0$.

![Figure 1. 2D and 3D geometry of the nozzle](image)

2.2. Mesh generation
To simulate the flow, the nozzle model is meshed by ANSYS ICEM. It is noteworthy that the flow of the nozzle jet is a centrally axisymmetric, the model is split and acquired in the case of a 3-degree circumferential angle (1/120 of the whole model). This approach is advantaged as the calculation is remarkably simplified, bespeaking that the convergent results can be promptly attained, thus facilitating the adjustment and optimization of the grid. In the meantime, no evident deviation shall be triggered via this simplified approach. Via this approach, the cases of a various combination of nozzle and spear angle can be rapidly acquired, a combination of higher efficiency can be selected, and thereupon the calculation of the $360^\circ$ whole model can be conducted. Accordingly, the manpower and material resources can be effectively saved. The mesh of nozzle model is structured grid as in the following figure.
To be simplified, the model is split into the front part of the nozzle domain and the latter part of the air domain. The grid number of the first half domain is smaller. The mesh is refined at the domain interface, places near the wall and the air-water interface. These grids are regulated repeatedly in the light of the calculation result to ensure that the mesh used can completely cover the air-water interface line. The final number of grid units used for the $3^\circ$ model mesh is 29,000.

2.3. Boundary conditions and simulation setup
The initial flow calculation is carried out using the ANSYS CFX software. The total pressure at inlet is 10791000Pa (1100m head). The exit and air area are free, and the walls are assumed to be smooth. This calculation is in line with steady flow, ignoring the gravity, the temperature of 25 $^\circ$C in the case of the conditions, using the SST $k-\omega$ model at the medium turbulence intensity.

2.4. Group of cases
The paper lays particular stress on the impact exerted by nozzle and needle angle in terms of the efficiency of the jet. Accordingly, a group of cases is set for this study. These cases encompass four different nozzle angles – $80^\circ$, $90^\circ$, $100^\circ$, $110^\circ$, three different needle angles - $50^\circ$, $60^\circ$, $70^\circ$, and three different strokes under each needle angle.

To make the results comparable, it is of great necessity to have a same mass flow in the case of different strokes. Therefore, a set of calculations of the flow area is conducted, their strokes are performed correspondingly, and thereupon a set of similar flow area is selected to ensure the mass flow to be acquired is roughly the same. Ensuring equal flow area, the parameters selected to be acquired in this study are as follows.

| Nozzle angle($^\circ$) | Needle angle($^\circ$) | Stroke/mm |
|-----------------------|-----------------------|-----------|
| 80                    | 50                    | 55        |
| 80                    | 60                    | 135       |
| 90                    | 50                    | 210       |
| 90                    | 60                    | 45        |
| 100                   | 50                    | 110       |
| 100                   | 60                    | 40        |
| 110                   | 70                    | 95        |
| 110                   | 145                   |           |

The cases to be acquired, therefore, shall be a total of $4$(nozzle angles) $\times$ $3$(needle angle) $\times$ $3$(stroke)$=36$.
3. Analysis and optimization of numerical simulation results

3.1. Simulation results of flow field

In the light of the foregoing results, cases of each group is modeled, meshed and acquired. The approach to mesh and compute settings is illuminated previously. Take 100°/70° combination as an example. The flow field in the nozzle mechanism are indicated from the results, comprising the total pressure distribution and velocity distribution.

![Figure 3. Water volume fraction cloud diagram with its corresponding grid (3°)](image)

![Figure 4. Global total pressure distribution cloud (3°)](image)

![Figure 5. Local total pressure distribution cloud (3°)](image)

The water-gas boundary line completely pertains to the grid encryption area through continuous adjustment. A jet area lies evidently from the nozzle at the outlet, generating a jet region of lower total pressure in the centre, which approaches to the fact.

3.2. Optimization of cases by efficiency

To ascertain the efficiency loss of the jet, the following formula is adopted in this subject:

\[
N = \int_A \left( p + \frac{\rho u^2}{2} \right) \rho u dA
\]
where the criterion energy $N$ is the integral of the total fluid pressure over the mass flow rate. The efficiency of the jet is acquired as follows:

$$\eta = \frac{N_{in} - N_{out}}{N_{in}}$$

The energy $N$ at the entrance of the nozzle mechanism denotes $N_{in}$, and the energy $N$ of the water at a distance of $4D_0$ (nozzle diameter) from the exit of the nozzle is $N_{out}$. The calculation results of flow rate and efficiency in the case of different cases are exhibited in the table below.

**Table 2. Numerical results of nozzle flow of different cases**

| Nozzle angle(°) | Needle angle(°) | Stroke /mm | Flow rate (m³/s) | $N_{in}/10^8$ (kg² m⁻¹ s⁻³) | $N_{out}/10^8$ (kg² m⁻¹ s⁻³) | Efficiency $\eta$/% |
|----------------|----------------|------------|------------------|-----------------------------|-----------------------------|-------------------|
| 80             | 55             | 2.054      | 1.84148         | 1.78442                    | 96.90                       |
|                | 135            | 3.971      | 3.55979         | 3.49667                    | 98.23                       |
|                | 210            | 4.737      | 4.24711         | 4.1765                     | 98.34                       |
| 60             | 45             | 2.05       | 1.83781         | 1.77099                    | 96.36                       |
|                | 110            | 3.924      | 3.51796         | 3.44217                    | 97.85                       |
|                | 170            | 4.691      | 4.20543         | 4.13435                    | 98.31                       |
| 70             | 40             | 2.141      | 1.91968         | 1.85066                    | 96.40                       |
|                | 95             | 3.95       | 3.54101         | 3.48015                    | 98.28                       |
|                | 145            | 4.698      | 4.21217         | 4.14761                    | 98.47                       |
| 90             | 55             | 1.988      | 1.78213         | 1.7118                     | 96.05                       |
|                | 135            | 3.858      | 3.45876         | 3.39727                    | 98.22                       |
|                | 210            | 4.614      | 4.13713         | 4.07227                    | 98.43                       |
| 60             | 45             | 1.988      | 1.78205         | 1.72049                    | 96.55                       |
|                | 110            | 3.815      | 3.4207          | 3.35018                    | 97.94                       |
|                | 170            | 4.559      | 4.08734         | 4.01796                    | 98.30                       |
| 70             | 40             | 2.112      | 1.89343         | 1.83944                    | 97.15                       |
|                | 95             | 3.854      | 3.45561         | 3.40306                    | 98.48                       |
|                | 145            | 4.532      | 4.06296         | 4.01407                    | 98.80                       |
| 100            | 55             | 1.928      | 1.72875         | 1.66104                    | 96.08                       |
|                | 135            | 3.751      | 3.36278         | 3.30316                    | 98.23                       |
|                | 210            | 4.492      | 4.02712         | 3.96324                    | 98.41                       |
| 60             | 45             | 1.929      | 1.72922         | 1.66212                    | 96.12                       |
|                | 110            | 3.709      | 3.32542         | 3.2535                     | 97.84                       |
|                | 170            | 4.437      | 3.97768         | 3.91246                    | 98.36                       |
| 70             | 40             | 2.049      | 1.83669         | 1.78564                    | 97.22                       |
|                | 95             | 3.748      | 3.3601          | 3.30825                    | 98.46                       |
|                | 145            | 4.424      | 3.9664          | 3.93208                    | 99.13                       |
| 110            | 55             | 1.871      | 1.67756         | 1.61157                    | 96.07                       |
|                | 135            | 3.655      | 3.27707         | 3.2164                     | 98.15                       |
|                | 210            | 4.383      | 3.93002         | 3.8614                     | 98.25                       |
| 60             | 45             | 1.872      | 1.67814         | 1.61617                    | 96.31                       |
|                | 110            | 3.616      | 3.24157         | 3.16987                    | 97.79                       |
|                | 170            | 4.325      | 3.87715         | 3.81289                    | 98.34                       |
| 70             | 40             | 1.99       | 1.7841          | 1.73497                    | 97.25                       |
|                | 95             | 3.649      | 3.27146         | 3.22006                    | 98.43                       |
Through adopting the results of the table, the efficiency comparison diagrams of different cases are processed and plotted, as exhibited in the following figure.

**Figure 6.** Efficiency comparison of different cases in the case of different flow rate (approximately 2, 4 and 4.5m$^3$/s)

On the basis of the foregoing calculation, it’s not difficult to find the most efficient nozzle and needle angle combination is 100°/70 °.

**4. Simulation of overall model**

To specifically illuminate this optimal combination, a 360° overall model is adopted for flow analysis. The setting of the periodic face is cancelled in the flow simulation, and the rest is the same as before. The cloud diagrams are shown below.

The parameters of the whole model are consistent with those of the 3 ° model. In the meantime, the rate of flow and energy criterion N are not more than 1% compared with the results of the 3 ° model, which further validates the reliability of the previous calculation results.

**Figure 7.** Water volume fraction cloud diagram with its corresponding grid (360°)
5. Conclusion
Given the analysis of the foregoing data and charts, the following conclusions can be drawn:

Nozzle mechanism with nozzle and needle angle of 100°/70° has the best overall jet efficiency.

In the light of the results, among the three factors – nozzle angle, needle angle and stroke, the needle angle has the biggest influence on jet efficiency, followed by stroke and nozzle angle.

Needle angle is not positively bound by the efficiency. The combination of needle angle 60° is adopted in this paper, whereas its efficiency evidently below the combination of needle angle 50° and 70° under the design discharge efficiency.

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