Influence of design parameters of discharge passage on the performance of shaft tubular pumping system

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Abstract. Shaft tubular pumping systems with straight discharge passage are more widely adopted because they possess many advantages such as easier installation of pump sets, better ventilation for motor and transmission devices, open access to inspect pump sets and lower cost for maintenance. The design parameters of a straight discharge passage will directly affect hydraulic loss and energy performance of the shaft pumping system. The optimal hydraulic design of discharge passages is carried out under the guideline of Pump Station Design Code to satisfy optimal design objectives. Computational fluid dynamics is applied to simulate the internal flow of a shaft pumping system the influence of its design parameter on the system performance is investigated. Keeping the shaft and suction box unchanged, six discharge passage design schemes with different length and outlet width are compared based on CFD to analyze the internal flow fields and their energy performances are predicted. The computed results indicate that when the outlet width of discharge passage is fixed, the longer the discharge passage, the better the internal flow fields with smaller backflow and vortex zone inside the passage. When the length of discharge passage is determined, the axial velocity distribution uniformity and bias angle in the outlet section will vary with the value of the outlet width. Optimal hydraulic design of discharge passages can achieve better internal flow and higher pumping efficiency.

1. Introduction
In the process of cities and towns enlargement, accompanied with more and more farmers rushed into cities to find better jobs and more economic development zones and industry parks emerged in suburbs of large cities, the situations of flood control for cities and towns become more and more serious. Among the hydraulic projects for municipal flood control, drainage pump stations with low or extra-low heads possess larger proportions [1-2]. Taking the flood control projects under construction or completed in Suzhou, Wuxi and Yancheng, Jiangsu province of China as examples, the drainage pumping heads are often less than 4 meters, and 50% of them are less than 2m, or even less than 1m[3-7]. Shaft tubular pump stations with straight discharge passage are widely adopted in the design and construction of municipal flood control engineering, due to their simpler hydraulic structure, easier
installation of pump sets, better ventilation for motor and transmission devices (if necessary), open access to inspect pump sets and lower cost for maintenance[8].

For low head pump stations the hydraulic loss of suction box and discharge passage will affect the pumping efficiency directly, optimal hydraulic designs are often employed and CFD simulation has become a current practice to optimize the hydraulic design and achieve higher pumping system efficiency. In this paper, the design parameters of shaft and suction box are kept unchanged that have been optimized in Ref.[9], six design schemes with different discharge passage length and outlet width are compared based on CFD to analyze the internal flow fields and predict their energy performances.

2. Objective for optimal hydraulic design of discharge passages

A pumping system is composed of a suction pipe, a pump and a discharge pipe. For a large and medium type low head pumping system the suction and discharge pipe are replaced by suction box and discharge passage, the purpose of which is to generate better flow conditions for pump and reduce discharge pipeline hydraulic loss. The discharge passage is a passage linking the outlet section of diffuser and the discharge pool, characteristic of shorter in length but more change in cross-section shape, the influence of its hydraulic loss upon the pumping system efficiency is more striking.

The optimal hydraulic design of discharge passages should be carried out under the guideline of Design Code for Pump Station (GB/T50265-2010)[10], and the following requirements should be satisfied. (a) The change of cross section in shape and size should be done smoothly and gradually. The value of diffusive angle in the longitudinal direction should be appropriately taken, usually within 8° to 12°, and avoid flow separation and vortex or other bad flow patterns inside the discharge passage. (b) The average velocity in the outlet section of the discharge passage should not exceed 1.5m/s to facilitate reclaiming dynamic energy of flowing water, and greater value is inadvisable. (c) The hydraulic loss of discharge passage should be reduced as much as possible [3].

3 Computation models for optimal hydraulic design of discharge passages

3.1 Optimal hydraulic design schemes of discharge passage

The study case comes from an alternative design scheme for a shaft type tubular pump station with straight discharge passage for municipal flood control, in which 3 tubular pump sets are installed, the designed net pumping head is 1.15m and the designed discharge for each pump is 10m³/s. The diameter of tubular impeller is 1.75m and the rotational speed of pump is 189.5 r/min [9]. In the previous design stage the selection of pump and optimal design of suction box has been completed within the specified water level and other civil control parameters.

When water flowing out of the outlet section of diffuser, it will be diffusing both in the direction of width and length. The passage length \( L \) and outlet width \( B \) of the discharge passage are vital parameters affecting its internal flow fields and hydraulic performance. The equivalent diffusing angle \( \alpha \) on each side of the passage shown in Figure 1 can be easily calculated out when other relevant design parameters are given.

![Figure 1. Design parameters of straight discharge passage.](image-url)
For the study case, based on the lowest water level in the discharge pool and minimum submerging depth above the outlet section of discharge passage, the outlet height is taken 2.2m and the inlet diameter is 1.86m, respectively. There are two choices of outlet widths of 5.0m and 5.6m, and the average outflow velocity is between 0.81m/s and 0.91m/s, meeting the specifications given in the Design Code [9]. Combined with three different passage lengths of 11.2m, 13.0m and 15.2m, there are six design schemes of discharge passage in total, as given in Table 1.

| Scheme No. | 1     | 2     | 3     | 4     | 5     | 6     |
|-----------|-------|-------|-------|-------|-------|-------|
| Passage length L (m) | 11.2  | 13.0  | 15.2  | 11.2  | 13.0  | 15.2  |
| Outlet width B (m)   | 5.0   | 5.0   | 5.0   | 5.6   | 5.6   | 5.6   |
| Average diffusing angle α (deg) | 13.6  | 10.8  | 8.6   | 16.0  | 12.8  | 10.2  |

3.2 Governing equations and turbulence model
When a tubular pumping system is operating steadily, its internal flow can be regarded as three-dimensional steady incompressible viscous flow, and it can be described by the mass conservation equation and the time-averaged Navier-Stokes equations, and closed by the RNG $\kappa-\varepsilon$ turbulence model [8, 11-12].

3.3 Modeling and meshing of computation domain
Computation domains of with different schemes of straight discharge passage are formed in combination of shaft type suction box, tubular pump, as well as sump and discharge pool, and 3D models by means of Gambit and Pro/E is created in Figure 2(a). In order to save computation cost and raise prediction precision the numerical simulation and performance prediction of shaft tubular pumping systems are conduct based on model pumping system according to pump affinity and keeping the product of $nD$ unchanged, where $n$ is the rotational speed of pump and $D$ represents the diameter of impeller. Mixed meshes of structured and unstructured meshes are generated to adapt complex and curved shapes of the pumping system, and there are about 700,000 nodes for the whole computing domain as shown in Figure 2, and the mesh quality and independence solution of mesh size were checked before formal starting of numerical computations.

![Figure 2. 3D model of shaft tubular pumping system.](image)

4. Results and discussion

4.1 Internal flow analysis
According to the numerical simulation results of shaft tubular pumping system with six design schemes of discharge passage, the internal flow fields can be drawn out and compared. Figure 3 indicates that when the tubular pump and suction box are kept the same the internal flow in a straight discharge passage is totally affected by its design parameters, and for some designs obvious flow separation and vortexes can be seen. The inflow of the discharge passage comes from the outlet section of guide vanes, the velocity is quite high. When the water passes the discharge passage to the discharge pool, it doesn’t flow along the axial direction because of the existence of residual velocity circulation. As the cross-section area becomes larger and larger from the inlet to the outlet of the passage, the velocity slows down gradually.
Figure 3. Comparison of flow fields of different design schemes of discharge passage.

Except the influence of outflow and residual circulation from the diffuser, the diffusing angle is another key factor. Figure 3 indicates that the discharge length, the outlet width and the diffusing angle are interacted each other, and all of them are contributing to the internal flow fields of the discharge passage. When the outlet width is fixed, the longer the discharge passage the better of the internal flow patterns. If the width and height of the outlet section are kept unchanged, the smaller the diffusing angle the longer passage needed. Comparatively speaking, smaller diffusing angles and longer discharge passages are favourable for improving the internal flow patterns of straight discharge passage. However, reducing diffusing angle or increasing the length of the passage will inevitably increase its civil construction cost. Hence, the two sides of flow patterns and civil cost need to be balanced.

4.2 Axial velocity distribution in the outlet section

The effect of design parameters on the internal flow will finally be reflected in the flow fields of the outlet section. The computation results show that when the passage length is 11.2m and the outlet width is 5.0m there is about one-third of the outlet section area in the state of backflow, the maximum backflow velocity reaches 0.38m/s (Figure 4(a)). When the passage length is increased to 13.0m the backflow area is reduced to one-fourth although the maximum backflow velocity is not changed (Figure 4(b)). Computation results indicates that when the passage length is further added to 15.2m, the backflow area and maximum backflow velocity are
reduced to one-fifth and 0.28 m/s, respectively. When the outlet width is 5.6 m and the length of the discharge passage is increased from 11.2 m to 13 m, there appears no backflow any more in the outlet section.

(a) Scheme 1 (L=11.2m, B=5.0m)  (b) Scheme 2 (L=13.0m, B=5.0m)

(c) Scheme 4 (L=11.2m, B=5.6m)   (d) Scheme 5 (L=13.0m, B=5.6m)

**Figure 4.** Distribution curves of axial velocity in the outlet section (m/s).

Table 2 shows the relationship between the distribution uniformity of axial velocity in the outlet section and the design parameters, from which it can be seen that with the increase of passage length the maximum axial velocity and bias angle tend to be smaller, and the distribution uniformity improved when the outlet width of the passage is fixed. While the length is fixed, the narrow width schemes get smaller bias angle and higher distribution uniformity.

| Scheme No. | Outlet width (m) | Length (m) | Max. axial velocity (m/s) | Distribution uniformity (%) | Max. bias angle |
|------------|------------------|------------|--------------------------|-----------------------------|-----------------|
| 1          | 5.0              | 11.2       | 3.75                     | 7.57                        | 23.26           |
| 2          | 5.0              | 13.0       | 3.28                     | 17.82                       | 17.57           |
| 3          | 5.0              | 15.2       | 2.17                     | 35.21                       | 9.86            |
| 4          | 5.6              | 11.2       | 3.55                     | 6.00                        | 24.95           |
| 5          | 5.6              | 13.0       | 3.32                     | 12.24                       | 22.90           |
| 6          | 5.6              | 15.2       | 2.35                     | 30.97                       | 22.23           |

4.3 Performance prediction of shaft tubular pumping system
The internal flow is closely connected with the system performances. For a low head pumping system, 1.15 m in the study case, a smaller difference in hydraulic loss of suction box and discharge passage will result in obvious difference in pumping efficiency. Among the 6 hydraulic design schemes of discharge passage, scheme Nos. 1 and 4 achieve lower pumping efficiency, and scheme Nos. 2 and 5 achieve higher pumping efficiency. The performances of scheme Nos. 3 and 6 are not bad ones compared with scheme Nos. 2 and 5, but the improvement effect in pumping efficiency is not notable since the effect in improving internal flow by increasing the passage length, from 13.0 m to 15.2 m, may have been offset by the increased frictional head loss.

Based on the comparison of internal flow fields, pumping efficiency and civil cost and combined with the design parameters of suction box, the final adopted scheme is No.6 scheme. According to the prediction of energy performance (Figure 5) and taking the hydraulic loss of trash screen into consideration, the pumping system efficiency is about 61.0% when the net designed head is 1.15 m.
5 Conclusions

By applying CFD to simulate the internal flow of shaft tubular pumping system, through comparison of internal flow fields, axial velocity distribution in the outlet section of the passage and pumping system efficiency for six design schemes, the influence of its design parameters on the system performance are investigated.

(1) When the outlet width of discharge passage is fixed, the longer the discharge passage, the better the internal flow fields and the smaller backflow and vortex zone inside the passage.

(2) When the length of discharge passage is determined, the narrow width schemes get smaller bias angle and higher distribution uniformity.

(3) The final selection of optimal design scheme is based on the internal flow and hydraulic performance and other considerations as design parameters of suction box and civil construction cost.

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