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# Design and Structure Optimization of a Spiral Centrifugal Pump for Sludge Transportation

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**Abstract.** At present, the head of the existing spiral centrifugal pump in China is generally low, which can not meet the transportation requirements of sludge and other high viscosity medium. A new type of spiral centrifugal pump was designed, and its structure was optimized for the transport of high viscosity sludge. Through the numerical simulation of the internal flow, the flow and pressurization laws in the pump are revealed, and the vortex loss near the tail of the blade and the outlet pipe is found. The basic design requirements were achieved. Then the structure of spiral centrifugal pump was further optimized by adding a splitter blade, increasing the blade outlet angle, and improving the volute structure. With the efficiency remaining almost the same, the flow rate at the maximum efficiency point is increased by 20%, and the head has increased by 47% compared with the design value. The research results provide a reference for the technical improvement of sludge conveying spiral centrifugal pump.

**Keywords:** Spiral centrifugal pump; Design; Flow characteristics; Numerical simulation; Structural optimization.

## 1. Introduction

In recent years, domestic sludge production has been increasing year by year. Currently, oil-containing sludge from the petrochemical industry exceeds 10 million tons annually, while sludge discharge from industries such as steel, papermaking, and construction approaches 50 million tons, with significant contributions from municipal sludge as well. The original sludge has a high moisture content, and its collection and treatment processes require pumping. Furthermore, the rapid development of tunnel and bridge construction in China has led to frequent sludge pipeline transportation and transfer operations in tunnel construction and pile foundation projects [1,2]. Sludge is often characterized by high viscosity and significant impurities, making it challenging for conventional centrifugal and positive displacement pumps to meet transportation requirements. Centrifugal pumps are generally unsuitable for high-viscosity, high-solid-content fluids, while various types of positive displacement pumps always have relatively small flow rates and high costs, limiting their use in high-displacement applications [3].

Spiral centrifugal pump is a kind of impurity pump with special structure, the rotor is installed with spiral vanes, which can be divided into two parts, the spiral section and the centrifugal section, and this special structure makes it combine the advantages of positive displacement pump and centrifugal pump. And it has good anti-clogging performance, passing performance, suction performance and anti-cavitation performance. Due to the different uses of spiral centrifugal pumps involved in the research of scholars at home and abroad, the head of the existing spiral centrifugal pumps is relatively low, which can not meet the requirements of high viscous sludge transportation [4,5].

In this paper, a new type of spiral centrifugal pump was designed and improved for the objective to develop a high head spiral centrifugal pump, and the performance of the spiral centrifugal pump

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designed was analyzed by numerical simulation, which provides a reference for the development of a new type of sludge spiral centrifugal pump.

## 2. Key Parameters and Structural Design

### 2.1 Calculation of Key Impeller Parameters

The initial design flow rate of the pump is 250m$^3$/h, the head is 50m, and the rotational speed is 2000r/min. The structural parameters of the spiral centrifugal pump's impeller and the projection of the impeller axial surface are shown in Fig. 1. The contour line in axial surface of the impeller rim is straight line-circular arc-straight line in sequence, the contour line in axial surface of the hub is circular arc-straight line, and most of the spiral sections on the rim side adopt a conical design, which can ensure the uniformity of leaf tip gap in the process of operation very well.

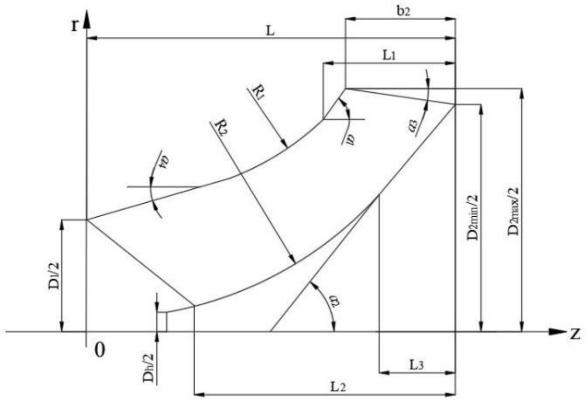

Fig. 1 Projection of impeller in the axial surface

Summarize and optimize the existing empirical expressions [6,7], and semi-empirical formulas, to get calculation methods for the main structural parameters of the impeller. Through reasonable calculation and preliminary optimization the structural parameters of the spiral centrifugal pump impeller are obtained, as shown in Table 1.

Table 1. Structure parameters of impeller

| notation | Numerical | notation | Numerical |
|---|---|---|---|
| $D_1$/mm | 190 | $\alpha_2$ / ° | 51 |
| $D_{2max}$/mm | 350 | $\alpha_3$ / ° | 8 |
| $D_{2min}$/mm | 315 | $\beta_{1,sh}$ / ° | 15 |
| $L$/mm | 278 | $\beta_{1,hu}$ / ° | 65 |
| $b2$/mm | 86 | $\beta_{2,sh}$ / ° | 15 |
| $d_h$/mm | 24 | $\beta_{2,hu}$ / ° | 18 |
| $\alpha_1$ / ° | 44 | $\varphi$ / ° | 630 |

### 2.2 Pump Structural Design

Based on projection diagram in axial surface of the impeller, the impeller structural parameters of the spiral centrifugal pump were substituted into the blade profile equations to get the complete contour line of impeller in axial surface, and the 3D profile of blade was drawn. Regarding the characteristics of sludge transportation, the passage property of solid particles was fully considered. And in order to adapt to the effect of the spiral impeller, on the basis of the existing design method of the volute, the spiral rise section at outlet section was increased and a rectangular cross-section was adopted. Thus the structure of axial suction and axial outflow for the pressurized water chamber was obtaied, and the axial helical rise angle of the pressurized water chamber is 6°.

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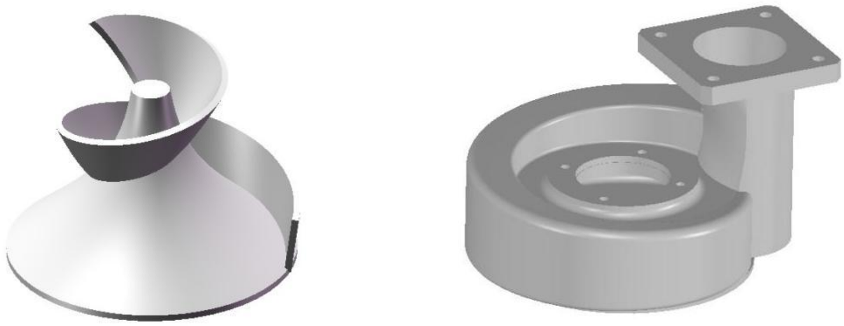
After obtaining the blade profile and the basic characteristics of the volute, Solidworks software was applied to the 3D modeling design of the spiral centrifugal pump. The impeller and the volute were partially solid modeling, as shown in Fig. 2. And it was found that the volute and the impeller are well matched.



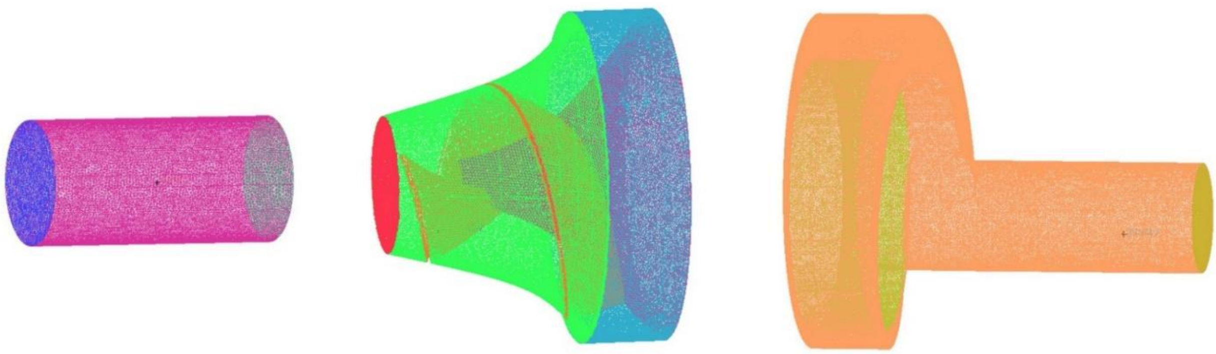
(a) impeller (b) volute

Fig. 2 D modeling of impeller and volute diagram

## 3. Calculation Method of Flow

### 3.1 Computational Modeling and Meshing

Extract and assemble the fluid domain for three-dimensional solid of the spiral centrifugal pump, and the fluid domain was simplified by ignoring the influence of blade tip clearance on pump performance. Divide the fluid domain of the entire spiral centrifugal pump into inlet domain, impeller domain, and volute domain, and extend the inlet and outlet pipes appropriately for stable flow at the inlet and outlet. Using ICEM software to partition the fluid domain into unstructured grids, then the three fluid domains are assembled in ICEM software. And the connection surfaces between the inlet pipe domain and the impeller domain, as well as between the impeller domain and the volute domain, are set as interfaces. The mesh division of the fluid domain of the spiral centrifugal pump is shown in Fig. 3.



(a) Grid for intake pipe (b) Grid for impeller (c) Grid for volute

Fig. 3 Fluid domain grid of the spiral centrifugal pump

### 3.2 Calculation Conditions and Boundary Settings

Based on the basic conditions of clear water medium at room temperature and a rotational speed of 2000 r/min, the flow rate was varied and the steady state MRF method was applied for numerical simulation using the RNG k-ε turbulence model. The velocity inlet and a natural outflow outlet

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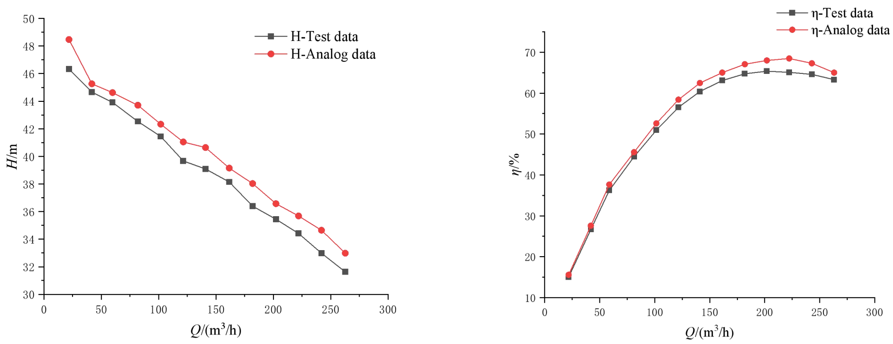
were also used. And a no-slip wall was used at the solid wall, and a standard wall function was used in the near-wall flow region.

### 3.3 Grid Independence and Result Correctness Verification

Comparison of the calculation results and comprehensive consideration of the calculation accuracy and calculation efficiency, it was found that the head of the spiral centrifugal pump tends to stabilize when the number of grids was greater than 1.95 million. And the subsequent calculation will be executed on a model with 1952880 grids. Based on the hydraulic test conditions of Jiangsu University [8] numerical simulation was carried out, and comparison of heads and efficiencies was shown in Fig 4. As seen in Fig 4, the numerical simulation results are basically consistent with the change rule of the test results, and the maximum error is 4.1%, so it can be considered that the numerical simulation methods and models are correct and reliable in this papper.

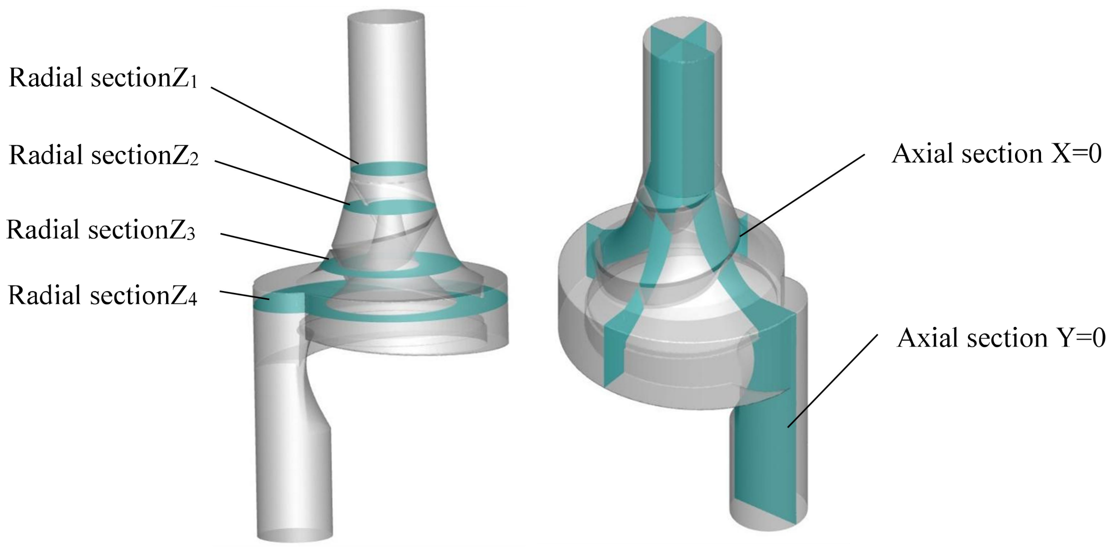



(a) Comparison of heads (b) Comparison of efficiencies

Fig. 4 Comparison of experimental values with numerical simulation results

## 4. Internal Flow and Pump Performance

Here four radial sections of different heights as well as two axial sections are selected to analyze the flow profile in the spiral centrifugal pump, which are radial section $Z_1$, radial section $Z_2$, radial section $Z_3$, radial section $Z_4$, axial section Y and axial section X, as shown in Fig. 5.




(a) Radial Sections (b) Axial Section

Fig. 5 Location of radial and axial feature sections

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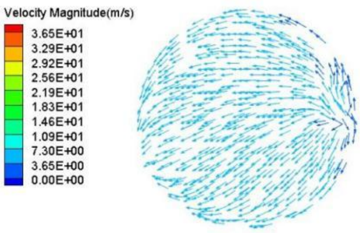
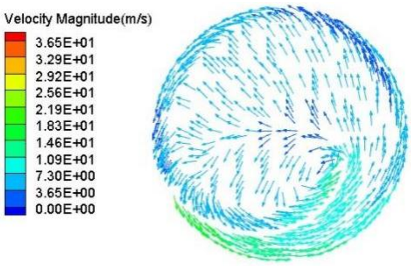
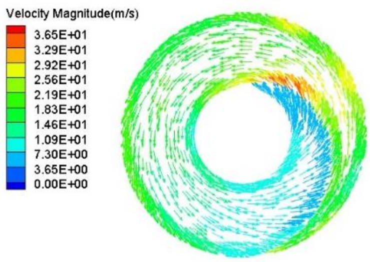
### 4.1 Velocity Profile

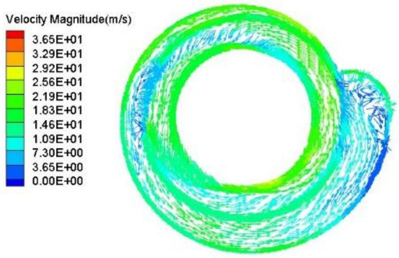
Fig 6 shows the velocity vector diagram in feature sections of the spiral centrifugal pump. From Fig. 6 it can be seen that as the fluid enters the impeller from the inlet section, the velocity gradually increases, and obvious spiral flow characteristics can be observed, indicating that the propulsion effect of the impeller's spiral blades enables the fluid to gradually obtain energy in the flow channel. From Fig. 6(d), it can be seen that there is a vortex at the end of the blade, which is due to the vortex caused by the trailing of the blade on the one hand, and on the other hand it is due to the large flow velocity at the exit of the blade, and the high speed fluid and the wall of the volute form an impact loss; it can also be found that there is an obvious vortex at the axial exit tube. The presence of significant swirls in this part of the region can be seen by the circles in Fig. 6(e) and Fig. 6(f). Therefore, the design of the volute profile is very important, not only to match the impeller discharge liquid flow, but also to consider the smooth transition of the axial outlet pipe to reduce losses.



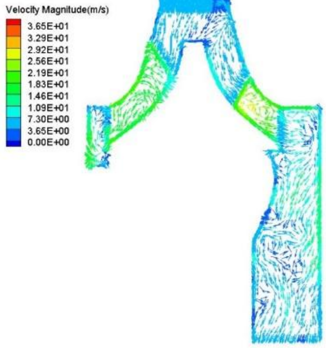



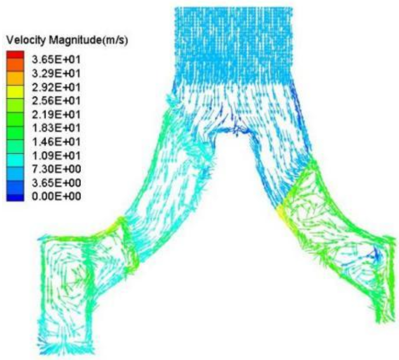

(a) Radial section $Z_1$ (b) Radial section $Z_2$




(c) Radial section $Z_3$ (d) Radial section $Z_4$






(e) Axial section Y (f) Axial section X

Fig. 6 Velocity vector diagram of feature sections

### 4.2 Pressure Profile

Fig 7 is the pressure contour map in radial sections of the spiral centrifugal pump; Fig 8 is the pressure contour map on the impeller surfac. As can be seen from Fig 7, the pressure from the inlet to the outlet cross-section of the pump increases significantly, and the pressure in the area of the outlet pipe is the highest. From Fig 8, it can be found that the pressure on the working surface of the blade is greater than that on the back of the blade, and there is a low-pressure area at the position of the blade inlet. And as the blade wrap angle gradually increases, the pressure on the surface of the

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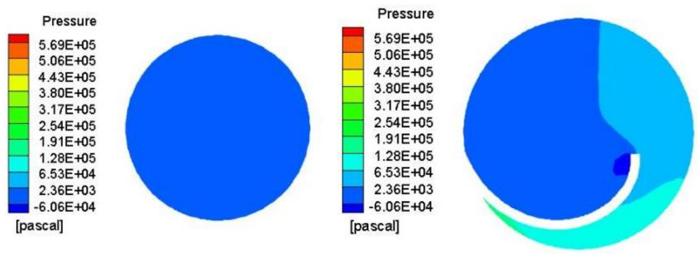
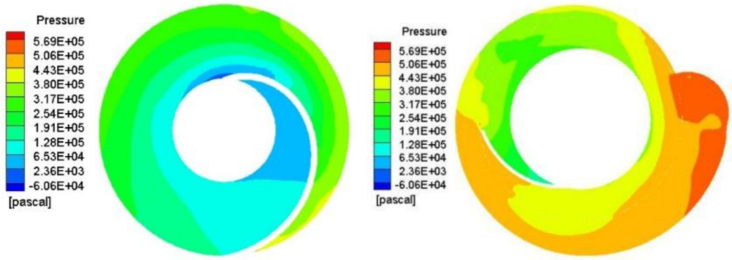
blade shows a gradually increasing trend. At the same time the pressure on the hub surface increases gradually along the radius direction, and the high pressure zone appears at the blade tail and hub edge. The pressure profile shows the energy conversion and pressurization process within the spiral centrifugal pump. It can also be found that the non-symmetry of the impeller results in a non-uniform distribution of the pressure on the impeller surface, which results in larger radial forces on the impeller.




(a) Radial section $Z_1$ (b) Radial section $Z_2$




(c) Radial section $Z_3$ (d) Radial section $Z_4$

Fig. 7 Pressure contour map of radial section

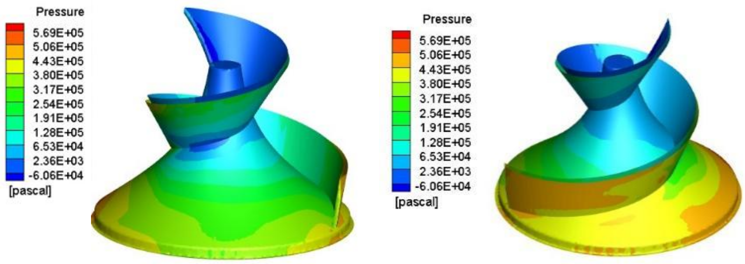



Fig. 8 Pressure contour map of impeller surface

### 4.3 External Characteristic Curve

Under the condition of room temperature clear water medium, change the flow rate for a number of steady state numerical simulation, the spiral centrifugal pump head, efficiency and shaft power characteristic curve was obtained, as shown in Fig 9.

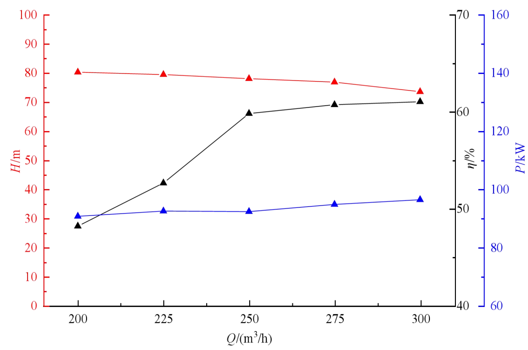



Fig. 9 Performance curves of basic model

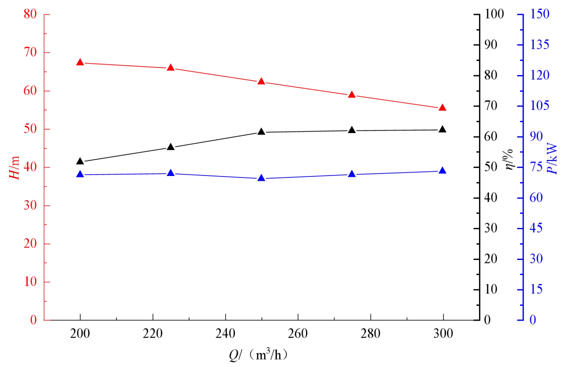



Fig. 10 Performance curves of optimized model

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As can be seen from Fig 9, with the increase in flow rate the power rises gradually and the head is showing a downward trend; at the highest efficiency point the flowrate is 250m$^3$/h, when the head is 62.2 m and the pump efficiency is 61.3%. The pump's high efficiency region is wide, and the basic design requirements were achieved.

## 5. Structural Improvement Exploration

On the basis of the aforementioned structure, further structural optimization was performed, including changing the blade outlet angle to 90 °, symmetrically adding a splitter blade with the wrap angle of 120°, and reducing the axial helix angle of volute to 3°. After calculation, performance curves of the combined optimization model is shown in Figure 10. It was found that the flow rate at the highest efficiency point becomes larger, which is 300m$^3$/h; and at this point the head is 73.5m and the efficiency is 61.2%. Compared with the basic type, the efficiency remains basically unchanged, but the flow rate and head have been improved, which is conducive to the transportation of sludge.

## 6. Conclusions

In response to the high head of the spiral centrifugal pump used for sludge transportation, a new type of spiral centrifugal pump was designed and structurally optimization was made. Through the numerical simulation of the internal flow, the flow and pressurization law in the pump was revealed, and the vortex loss at the end of the blade and near the outlet pipe was found. Further structural optimization was carried out on the pump, and with the efficiency almost the same the flow rate at the highest efficiency point was increased by 20%, and the head reaches 73.5m, which is 47% higher than the design value. The research results of the paper provide guidance for the development of spiral centrifugal pumps for sludge transportation

## 7. Acknowledgements

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