Numerical simulation and optimization of pulp pump

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Abstract. Pulp pump plays an important role in the transportation process of pulp and paper making industry. A CFD based investigation toward pump performance optimization was performed by using the commercial package CFX15.0. To improve accuracy, the grid irrelevance was examined by employing different mesh sizes. In addition, the simulations were performed at steady state with the RNG k-ε model. The comparisons between numerical and experimental results of the originally designed pump were further analyzed. It was showed that the head and efficiency were much lower than the expected performances. To optimize the pump performance, the Design of Experiments (DOE) method was further applied to improve the originally designed pump. The experiments with different outlet blade angles, impeller suction eye diameters, and volute widths were conducted. The results showed that the performance of the pump with smaller impeller inlet diameter and smaller volute inlet width was comparatively better. In addition, the head and efficiency was increased a little by increasing the blade outlet angle appropriately.

1. Introduction

The pulp pump poses an important position in paper-making process. With the development of paper-making industry, the requirement of technology innovation on pulp pumps is self-evident. The centrifugal pulp pump manufactured domestic is mainly used for transporting low consistency paper pulp. To avoid blocking, the centrifugal pulp is usually equipped with open or semi-open impeller, which means the front shroud or rear shroud is replaced by two wear plates. And the head and efficiency drop because of the existence of clearance between impeller and wear plates[1-3].

The flow mechanism is extremely complex and is still not clearly understood till now. It is difficult to carry out experiments to research the flow performance of paper pulp within pumps[4-5]. The two-phase flow theory and design method of centrifugal pump were proposed by Cai Bao-yuan[6], a professor of Tsinghua University, in the 1980s. The theory and method mainly lay the basis for designing of pulp pumps. Li Hong, a professor from Jiangsu University, Yang Jian-guo and many other people have made a lot of researches on the structure characteristics of pulp pump with open and semi-open impeller[7-10]. But the design of pulp pump still has a great dependency on the experiments, as well as the experience of designers. And a majority of the pump product was introduced from abroad[11].

To avoid blocking in flow channels, the pulp pump usually has fewer blades than normal centrifugal pump. So the efficiency is lower. Companies usually sacrifice efficiency to achieve higher head and better passing capability. The main problem of the existing pump product investigated in this research is that its head and efficiency are much lower than expected performance. Being restricted to the original structure and size specified by the product specification, many parameters cannot be changed.
To optimize the pump performance, the influence of outlet blade angle of impeller and inlet width of volute was studied in this research.

2. Numerical simulation

2.1. Basic pump parameters
The pulp pump under investigation in this research is equipped with an open impeller using three blades. The main design parameters are as follows: the flow rate \( Q = 100 m^3/h \), the pump head \( H = 17 m \), the rotating speed \( n = 1450 r/min \) and the specific speed \( n_s = 105.4 \). The originally designed pump has a 265mm diameter impeller. It’s geometrical parameters are as follows: the impeller inlet diameter \( D_1 = 129 mm \), the impeller exit width \( b_2 = 25 mm \), the blade outlet angle \( \beta_2 = 43^\circ \), the wrapping angle of blade is 133°, the base circle diameter of the spiral volute is \( D_c = 272 mm \), the discharge diameter of the spiral volute \( D_4 = 100 mm \), the inlet width of the spiral volute \( b_3 = 53 mm \). The flow media is pulp. At the preliminary study, pure water is used instead during simulations for comparison between numerical and experimental results. The assembly drawing of the originally designed pump is shown in figure 1 as follows.

![Figure 1. Assembly Drawing](image)

2.2. Mesh generation
The flow channel of pump is constituted by suction pipe, impeller, spiral volute, clearance cavity and discharge pipe. The length of suction pipe extension is three times of inlet diameter and the length of discharge pipe extension is two times larger than the diameter.

There are certain clearances between the impeller and wear plates. Researches showed that the size of clearance between impeller and wear plates have great impact on head and efficiency of pump[14]. According to the assembly drawing of originally designed pump, clearance between impeller and wear plates was both set at 0.5mm. The computational domain becomes much complex when taking clearance into consideration.
For complexity of the computational domain, the unstructured grids are set up by ICEM CFD15.0. To avoid influence of mesh size on numerical results, the mesh size of computational domain was set separately at 3.0mm, 4.0mm, and 5.0mm. The computational results showed that, the head and efficiency of pump was basically the same after decreasing mesh size up to 4.0mm. And considering computational expense, the mesh size was finally set at 4.0mm.

| Mesh size/mm | 3.0   | 4.0   | 5.0   |
|--------------|-------|-------|-------|
| Total elements | 9065287 | 2900110 | 1710081 |
| Efficiency(%)  | 73.06   | 73.20   | 73.37   |
| Head(m)        | 17.93    | 17.90    | 17.79    |
| Iteration steps | 1260     | 1190     | 1119     |

2.3. Operating conditions and boundary conditions
The simulations were conducted on the platform of ANSYS CFX15.0. The normal speed was set at the pipe inlet computed from the pump flow rate. The average static pressure was specified at outlet. And the RNG $k-\varepsilon$ turbulent model was enabled for all optimization schemes[11-13].

3. Computational Results and Analysis

3.1. Computational results and experimental results of originally designed pump
The pump was made and tested by Shang Bao Luo Pump Co.Ltd. The test results are shown in figure 4. The peak efficiency approaches 53% at the flow rate of 120m³/h. The head at operation point reaches 13.86m, which is 18.5% lower than target head.

Based on the numerical simulations, the head is calculated as follows:

\[
H = \frac{(P_{\text{tot}} - P_{\text{in}})}{\rho g}
\]

Where \(P_{\text{tot}}\) is the total pressure at outlet, and \(P_{\text{in}}\) is the total pressure at inlet.

Then the efficiency is calculated as follows:

\[
\eta = \frac{\rho g Q H}{M \omega}, \quad \eta = \eta_{h} \times \eta_{v} \times \eta_{m}
\]

Where \(M\) is the torque of pump impeller, \(\omega\) is the angular velocity of the impeller, \(\eta\) is the efficiency of pump, \(\eta_{h}\) is the hydraulic efficiency of pump, \(\eta_{v}\) is the volume efficiency of pump, and \(\eta_{m}\) is the mechanical efficiency of pump. In this paper, \(\eta_{v} = 0.8\) and \(\eta_{m} = 0.9\).

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**Figure 4.** Originally designed pump performance curves

**Figure 5.** Head vs. flow rate curves

**Figure 6.** Efficiency vs. flow rate curves
Figure 5 and figure 6 show the head and efficiency characteristic curves from experiments and computations. It can be seen that there is a considerable discrepancy between the computational results and the experimental data. The simulation result is theoretical head and efficiency precluding volumetric and mechanical losses. When taking the clearance into consideration, the head approximately decreased by 1.3m and the efficiency reduced nearly by 2%. This loss is commonly counted into the volumetric efficiency. But the mechanical efficiency including the disk friction loss could not be accurately simulated. In practice, the head drop due to higher clearance by assembly error and wear between impeller open blade faces and plates will be even greater than simulations.

3.2. Influence of blade outlet angle
The performance of pump is mainly affected by such factors as the inlet diameter of impeller, the outlet diameter of impeller, outlet blade angle, etc. However, many parameters cannot be changed because of the requirements of the specified product size and cost. By setting the outlet blade angle to 40°, 52°, 55°, separately, the corresponding simulations were performed and their performance curves are shown in figure 7 and figure 8, as follows.

![Figure 7. Head vs. flow rate curves](image1)

Figure 7. Head vs. flow rate curves

![Figure 8. Efficiency vs. flow rate curve](image2)

Figure 8. Efficiency vs. flow rate curve

It can be seen from figure 7 and figure 8, the head raises with the increasing of outlet blade angle. Whereas the change of efficiency is not obvious.

3.3. Influence of volute

![Figure 9. Head vs. flow rate curves](image3)

Figure 9. Head vs. flow rate curves

![Figure 10. Efficiency vs. flow rate curves](image4)

Figure 10. Efficiency vs. flow rate curves

\[ b_3 = b_2 + 2(\delta \pm 1) \]
When designing semi-opened pulp pump, the inlet width of the spiral volute is usually decided according to outlet width of impeller and the thickness of wear plates. Flow diffusion loss increases with the increasing volute size. The inlet width of redesigned volute is 38mm, and the inlet diameter of new impellers is 110mm. The outlet blade angle of three new computational models are 40˚, 44˚, 49˚. It can be seen from Figure 9 and Figure 10, the head increase but the efficiency decrease with the increasing of outlet blade angle.

![Static Pressure Distribution](image1.png)

**Figure 11.** The static pressure distribution for two volute at the specified flow rate

![Velocity Vector Diagram](image2.png)

**Figure 12.** The velocity vector diagram for two volute at the specified flow rate

From Figure 11 and Figure 12, the static pressure distribution is smoother in new volute, especially at the area around the tenth cross-section. In the bigger volute, the velocity drops rapidly. When the outlet blade angle is the same, the hydraulic loss in smaller volute is lower.

4. **Conclusion**

The centrifugal pulp pump is an indispensable part in paper-making process. Pumps consume almost 30 percent of the total electricity used in a paper mill. In the past, the head and efficiency were put in the secondary position because of the requirement for passing capability. Thus the performance improvement of pumping system is critical for energy-saving in paper-making industry.
To improve the head and efficiency of the pulp pump investigated in this research, a series of designing models with different outlet blade angle and the inlet width of volute were studied. According to the computational results, the head was improved with the increasing of outlet blade angle, but the efficiency was decreased. When the impeller was equipped with smaller volute, the head and efficiency improved obviously. In general, these results also provide evidence and choice for manufacturers by adopting slightly bigger outlet blade angle and smaller volute to improve the hydraulic performance in their pump products.

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