

Study on Performance Characteristics and Influencing Factors of Four-outlet Centrifugal Pump

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Abstract: In order to study the influence of different geometric parameters and performance parameters on the external characteristics and outlet head uniformity of a single-stage multi-outlet centrifugal pump, a certain single-stage four-outlet water pump was chosen as the research object. Under the premise of keeping all parameters except the target parameter constant, the number of impeller blades, outlet width, and mass flow rate at the outlet were studied separately to explore the variation trends of the average pressure fluctuation rate and average head when the number of blades changed from 5 to 8. The study was combined with numerical simulation calculations. The research showed that as the number of blades increased, the head of the centrifugal pump gradually increased. When the number of blades was between 5 and 7, the increase in head was more significant, with an increase of 0.61m. When the number of blades increased to 8, the increase in head became relatively gentle, with only a 0.17m increase. When the impeller blades increased from 5 to 6, the pressure fluctuation rate at the outlet decreased by 0.4%. When the number of blades increased to 7, the pressure fluctuation rate decreased by 1.85%. When the number of blades increased to 8, the pressure fluctuation rate decreased by 0.8%. When the outlet width changed from 5.2mm to 6.7mm, the head increased by 0.4m, with an increase of 6.4%, and the pressure fluctuation rate at the outlet decreased by 2.9%. As the outlet flow rate increased from 15L/min to 30L/min, the head of the centrifugal pump decreased by 1m, and the pressure fluctuation rate at the outlet increased by 3.4%, indicating an increasing difference in head among the outlets.

Keywords: Four Outlet Centrifugal Pump; Impeller Outlet Width; Number Field of Leaves; Numerical Simulation.

1. Introduction

In the cooling system of a piston engine, a multi-outlet centrifugal pump is used to individually cool each cylinder, and there is a high requirement for the uniformity of the head at each outlet. However, in practical engineering applications, due to the engine's requirements and size limitations, it is often not possible to distribute the multi-outlet centrifugal pump evenly at the same angle, resulting in inconsistent pressure losses at each outlet and a significant difference between the uniformity of the head distribution and the target value. Therefore, studying the influence of various parameters on the uniformity of the head distribution in a multi-outlet centrifugal pump has practical engineering guidance significance. Similar to a single-outlet centrifugal pump, the head, efficiency, and other external characteristics of a multi-outlet centrifugal pump are determined by important flow components such as the impeller and volute. Any variation in geometric parameters can affect the internal flow field and consequently impact the pump's external characteristics [1-3]. Guo et al. [4] studied the influence of the inducer clearance on the high-speed performance of a centrifugal pump under different flow conditions. The study showed that at high flow rates, the head and efficiency of the centrifugal pump are significantly affected by the inducer clearance, with an increase in clearance leading to an increase in head and efficiency. Wang et al. [5] investigated the effect of blade geometry parameters on the performance characteristics of a centrifugal pump at medium specific speeds and found that as the length of the blades decreases, the head and efficiency also decrease. Zhao et al. [6] studied the impact of different blade parameters on the external characteristics of the pump and found that within a certain range of blade thickness variation, increasing the blade thickness slightly improves the maximum efficiency of the

centrifugal pump. Shang et al. [7] examined the influence of the number of blades on the performance of a centrifugal pump and found that within a certain range, appropriately increasing the number of impeller blades can effectively improve the stability of liquid flow and significantly enhance the external characteristics. Wan et al. [8] investigated the impact of the outlet width of impeller blades on the external characteristics of a centrifugal pump and found that within a certain range of blade width variation, an increase in outlet width leads to an increase in head, along with an increase in impeller pressure and a decrease in turbulence energy inside the flow passage. Currently, there is more research on the influence of geometric parameters on the performance of single-outlet centrifugal pumps, while there is limited research on the impact of a single factor on the head distribution of multi-outlet centrifugal pumps. In order to study the influence of geometric parameters and performance parameters on the uniformity of the head distribution in multi-outlet centrifugal pumps, this study is based on the design and development of a single-stage four-outlet water pump for a certain model of aircraft piston engine cooling system. By changing parameters such as the number of impeller blades, impeller outlet width, and outlet mass flow rate, the head is calculated using numerical simulation and centrifugal pump design theory. By comparing the average fluctuation rate of outlet pressures under different parameters, the study investigates the influence of a single factor on the uniformity of the head distribution in a multi-outlet centrifugal pump, providing reference for the design of multi-outlet centrifugal pumps.

2. Calculation Methods and Models

2.1. Model establishment and grid division

The centrifugal pump has the following basic parameters:

impeller outer diameter $D_2=52\text{mm}$, number of blades $Z = 7$, inlet diameter $D_1=22\text{mm}$, impeller outlet width $b_2=6.7\text{mm}$, 4 outlets, head $H=6.5\text{m}$, rotational speed $n=4766\text{r/min}$, and flow rate $Q=15\text{L}\cdot\text{min}^{-1}$. A three-dimensional model of the centrifugal pump was created based on the initial design, while keeping the other geometric parameters unchanged. Additional impeller models were established by modifying the number of blades to 5, 6, and 8, and the impeller outlet width to 5.2 mm, 5.7 mm, and 6.2 mm, respectively. Taking the initial design model with $b_2=6.7\text{mm}$ and 7 blades as an example, the three-dimensional fluid computational domain model is shown in Figure 1.

After completing the establishment of the three-dimensional model, Fluent Meshing was used for meshing. Unstructured hybrid tetrahedral meshes were selected, with local refinement at the blade and volute tongue positions. Taking the case of 7 blades as an example, the total number of mesh elements was 2,485,413.

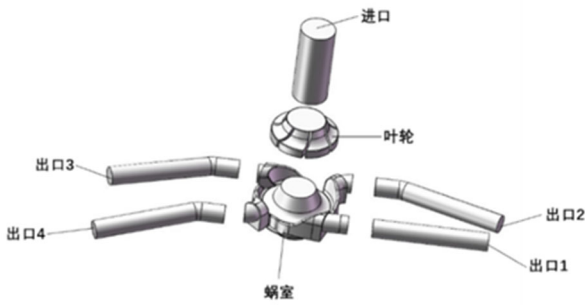


Figure 1. Fluid domain model

2.2. Method of calculation

The $k-\varepsilon$ turbulence model is used in this calculation. The standard $k-\varepsilon$ model ignores the influence of molecular viscosity on turbulence. It is assumed that the fluid flow is completely turbulent, so the turbulence model is only applicable to the case of complete turbulence. The $k-\varepsilon$ model is expressed by turbulent kinetic energy k and turbulent dissipation rate ε . The equation of turbulent dissipation rate ε is:

$$\varepsilon = \frac{\mu}{\rho} \left(\frac{\partial u_i}{\partial x_k} \right) \left(\frac{\partial u_j}{\partial x_k} \right) \quad (1)$$

The turbulent viscosity u_t is a function of k and ε :

$$u_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (2)$$

The transport equation corresponding to k is:

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} G_K - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \quad (3)$$

$$G_K = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (4)$$

where is the empirical constant of C_μ , G_K represents the turbulent kinetic energy caused by the average velocity gradient, C_μ is a constant, and the empirical value of each constant can be taken as $C_\mu = 0.09 \sim 0.11$, $\sigma_\varepsilon = 1.3$, $C_{\varepsilon 1} = 1.41 - 1.45$, $C_{\varepsilon 2} = 1.9 - 1.92$.

The impeller fluid domain is set to the rotating domain, and the other part is the stationary domain. The near-wall region is processed by the standard wall function method. The inlet type is set as the pressure inlet, and the four outlet types are all the mass flow outlets. The COUPLE algorithm is selected for the coupling of velocity and pressure, and the standard initialization of the inlet is performed [9-10].

3. Analysis of Simulation Results

3.1. Analysis of external characteristic curve

The calculation formula of head and efficiency of centrifugal pump is as follows [11]:

$$H = \frac{P_{out} - P_{in}}{\rho g} + \Delta Z \quad (5)$$

$$\eta = \frac{\rho g Q H}{M \omega} \quad (6)$$

The P_{out} is the total pressure at the outlet of the centrifugal pump, the P_{in} is the total pressure at the inlet of the centrifugal pump and the unit is pa; ΔZ is the height difference between the inlet and outlet of the centrifugal pump, the unit is m; M is the torque generated by rotation, unit is $N\cdot m$; ω is the angular velocity of the impeller rotation, the unit is rad/s .

Because the four outlets of the centrifugal pump involved in this paper are not evenly distributed according to the same angle, the calculated head has certain differences, but the errors are within the acceptable range of the actual project. In order to further explore the influence of various parameters on the external characteristics, the external characteristic curves of Q under different geometric and performance parameters are calculated by CFD, and the calculated head data are averaged.

It can be seen from Fig.2 that as the outlet width of the impeller increases, the head of the centrifugal pump also increases. This is because as the outlet width increases, the flow capacity of the fluid in the impeller increases, so that the flow of the fluid in the impeller is more uniform. The outlet velocity triangle at the outlet can also be analyzed. When the outlet width of the impeller increases, the circumferential velocity will also increase, resulting in an increase in the head of the centrifugal pump.

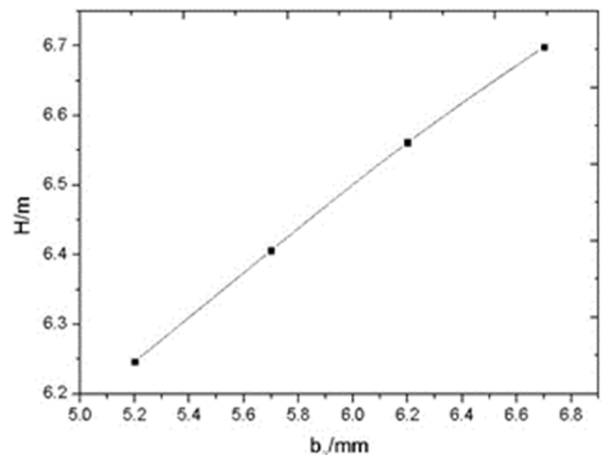


Figure 2. External characteristic curves for different outlet widths

It can be seen from Fig.3 that the head decreases with the increase of flow rate. When the flow rate is $15\text{L}\cdot\text{min}^{-1}$ - $18\text{L}\cdot\text{min}^{-1}$, the head decreases by 0.04m ; When the flow rate is $21\text{L}\cdot\text{min}^{-1}$ - $24\text{L}\cdot\text{min}^{-1}$, the head decreases by 0.37m ; when the flow rate exceeds $18\text{L}\cdot\text{min}^{-1}$, the increase trend of the centrifugal pump head becomes severe. As shown in Formula (6), when the efficiency is certain, the head of the pump is inversely proportional to the flow rate, which indicates that the trend of the numerical simulation results is in line with the general design principle of the pump and has certain reference.

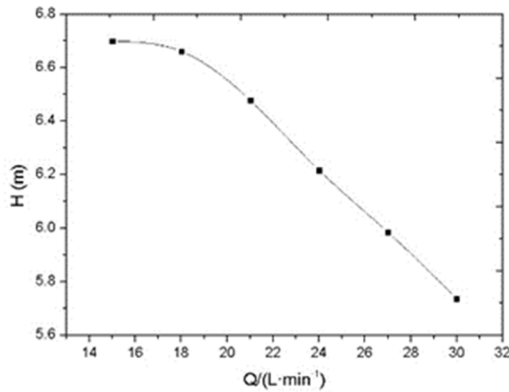


Figure 3. External characteristic curves of different flow rates

It can be seen from Fig.4 that when the number of blades of the impeller increases, the head of the centrifugal pump also increases. When the number of leaves is 5-7, the increase trend of the head is more intense, and the increase is 0.61m ; when the number of blades increases to 8, the lifting trend of the head is relatively gentle, with only a 0.17m increase. The head of the centrifugal pump is essentially produced by the blade work. The more the number of blades, the stronger the ability of the centrifugal pump to work on the fluid, and the head also increases.

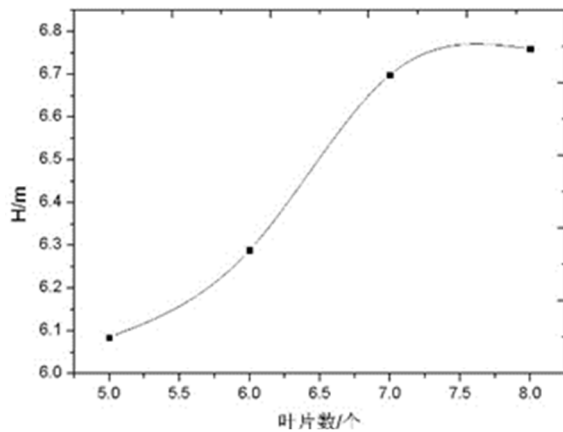


Figure 4. External characteristic curves for different blade numbers

3.2. The influence of outlet mass flow rate on outlet pressure fluctuation rate

Due to the particularity of the design boundary of the four-outlet pump involved in this paper, the four outlets are not evenly distributed according to the same angle. Therefore, outlet 1 is selected as the benchmark to calculate the pressure fluctuation rate of other outlets compared with outlet 1, and then the mean value is taken to characterize the change of outlet affected by mass flow, impeller outlet width and

impeller blade number, and to explore the influence of various performance parameters and geometric parameters on the uniformity of the centrifugal pump outlet head.

Figure 5 is the pressure distribution cloud diagram of the centrifugal pump section. It can also be observed from the cloud chart that in the small flow range, the pressure distribution of the whole flow field is relatively uniform, and there is no obvious increase in the pressure at a certain outlet. However, under the outlet flow conditions of $21\text{L}\cdot\text{min}^{-1}$ and $24\text{L}\cdot\text{min}^{-1}$, the pressure distribution at each outlet is obviously uneven, which eventually leads to the uneven distribution of the outlet head. Figure 6 shows the variation curve of the average outlet pressure fluctuation rate with the outlet mass flow rate. The pressure fluctuation rate increases with the increase of the outlet flow rate. When the outlet flow rate changes from $15\text{L}\cdot\text{min}^{-1}$ to $18\text{L}\cdot\text{min}^{-1}$, the outlet pressure fluctuation changes 0.64% . When the outlet flow rate changes from $21\text{L}\cdot\text{min}^{-1}$ to $24\text{L}\cdot\text{min}^{-1}$, the pressure fluctuation changes more violently, and the fluctuation rate increases by 1.85% .

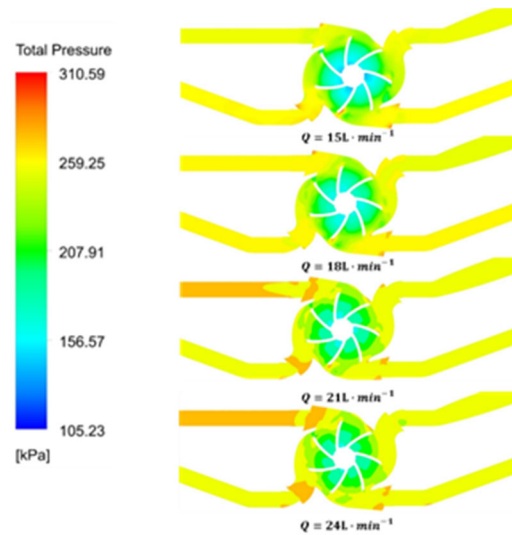


Figure 5. Cross section pressure distribution of centrifugal pumps with different flow rates

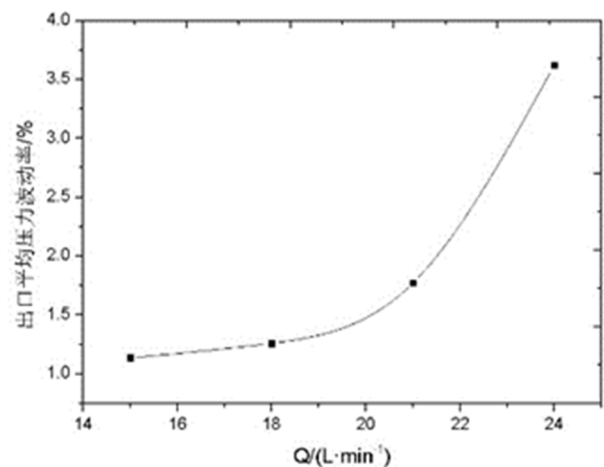


Figure 6. Fluctuation rate of outlet pressure at different flow rates

3.3. Effect of impeller blade number on outlet pressure fluctuation rate

In order to study the influence of the number of impeller blades on the uniformity of outlet head, control other geometric parameters unchanged, the performance

parameters are set according to the design standard, and the models with 5,6,7 and 8 impeller blades are designed respectively. Calculate the average pressure fluctuation rate of the outlet, the pressure cloud distribution of the centrifugal pump section and the change of the outlet fluctuation rate are shown in Figure 7 and 8.

It can be seen from Fig.7 that when the number of blades of the impeller is 5, the uneven distribution of pressure at the outlet is more significant, and gradually increasing the number of blades can effectively improve this phenomenon. When the number of blades increases, the flow distribution of each outlet in the unit rotation is more uniform, and the phenomenon of local pressure increase at the outlet is obviously improved. From Figure 8, it can be seen that with the increase of the number of impeller blades, the average pressure fluctuation rate of the outlet of the centrifugal pump is decreasing. When the number of impellers Z changes from 5 to 6, the pressure fluctuation rate at the outlet decreases by 0.4 %. When the number of blades increases to 7, the pressure fluctuation rate decreases by 1.85 %. When the number of blades increases to 8, the pressure fluctuation rate decreases by 0.8 %. Therefore, when the number of impeller blades increases, it can effectively improve the stability of liquid flow, and has a significant effect on the uniformity of head distribution at multiple outlets of centrifugal pump.

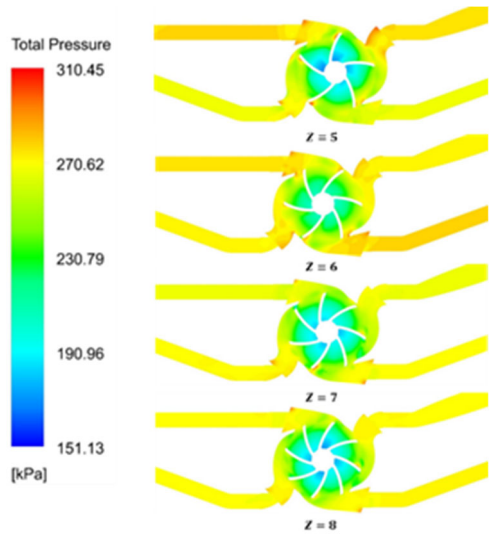


Figure 7. Cross section pressure distribution of centrifugal pumps with different blade numbers

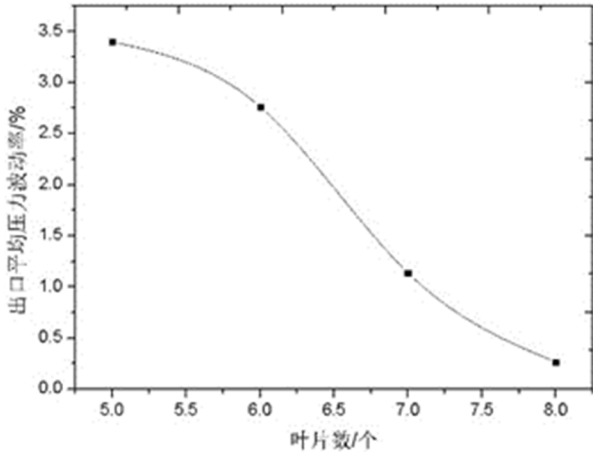


Figure 8. Fluctuation rate of outlet pressure at different blade numbers

3.4. The influence of impeller outlet width on outlet pressure fluctuation rate

Under the condition of controlling the number of blades, outlet flow and other performance parameters and geometric parameters unchanged, four sets of impeller models with different outlet widths are set up, which are $b = 5.2\text{mm}$, 5.7mm , 6.2mm and 6.7mm respectively, to explore the influence of the single geometric parameter on the average pressure fluctuation rate at the outlet.

It can be seen from Fig.9 that the low pressure area at the impeller inlet increases with the increase of the blade outlet width. The pressure distribution of the internal section of the whole centrifugal pump is gradually uniform, that is, the uniformity of the head is gradually increasing.

As shown in Fig.10, the average pressure fluctuation rate at the outlet decreases with the increase of the impeller width. When the impeller outlet width increases from 5.2mm to 5.7mm , the outlet pressure fluctuation rate decreases by 0.43% , and the decline rate is faster. When the impeller width is 5.7mm - 6.7mm , the outlet pressure fluctuation rate is reduced by 0.15% , and the overall change is gentle. When the outlet width of the impeller increases, the flow area of the fluid increases, which makes the fluid flow in the volute more stable, and finally the head distribution at each outlet gradually becomes uniform.

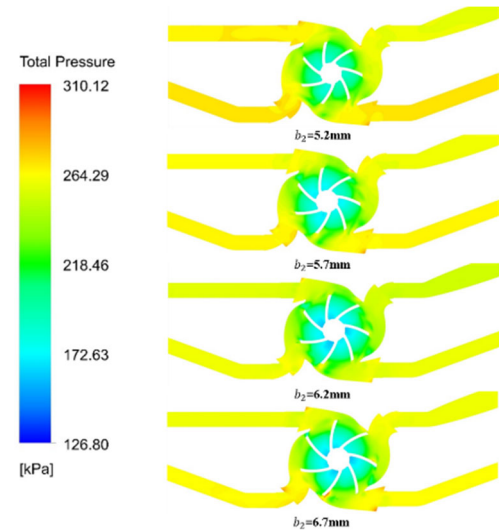


Figure 9. Cross section pressure distribution of centrifugal pumps with different outlet widths

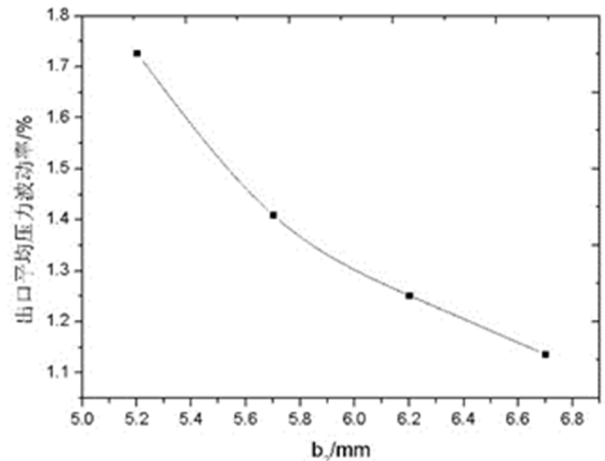


Figure 10. Fluctuation rate of outlet pressure at different outlet widths

4. Experimental Verification

According to the initial design parameters, a centrifugal pump with a blade number of 7 and an outlet width of 6.7mm was selected as the test pump body to build a test bench. Test the head of the pump body under different flow rates; the head is used as the intermediate value to analyze the accuracy of the numerical simulation data. The comparison between the experimental value and the calculated value is shown in Fig. 11. The maximum error of the calculation result is 3.47 %, which basically conforms to the accuracy of the engineering calculation.

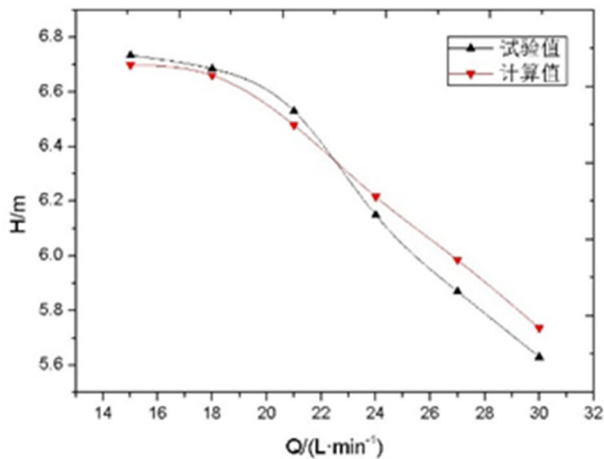


Figure 11. Comparison of head test value and calculated value

5. Summary

(1) Increasing the number of blades and impeller width in a certain range can improve the head of the centrifugal pump. The head of the centrifugal pump gradually decreases with the increase of the flow rate.

(2) For the single-stage multi-outlet centrifugal pump designed in this paper, with the increase of flow rate, the head distribution uniformity of each outlet is gradually decreasing, that is, the head difference between each outlet is gradually increasing.

(3) When the number of blades and the outlet width of the impeller are increased within a certain range, it will be found

that the head uniformity of each outlet is increasing, that is, the difference between the outlets is gradually decreasing, and when the number of blades changes from 6 to 7, the fluctuation rate is reduced by 1.85 %, and the effect is better.

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