Parameter optimization of centrifugal pump impeller

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Abstract. After the hydraulic calculation of the centrifugal pump, some design parameters of the impeller can be obtained. The axial projection of the impeller can then be drawn by conventional methods, but in the process, the determination of some parameters in the axial projection map ignores whether it is an optimal solution. In this paper, orthogonal test method is used to determine the optimal solution and optimal combination of some design parameters in the axial projection map, to achieve multi-objective optimization, and to optimize the axial projection of the impeller, improve the flow curve of the impeller and improve work efficiency.

1. Introduction
At present, most of the centrifugal pump design methods are based on the one-way theory and the similarity theory based on the model-changing algorithm and the velocity coefficient method [1]. The core component of the centrifugal pump is the impeller, and the efficiency of the pump depends mainly on the shape of the impeller. The shape of the impeller is mainly determined by the axial projection of the impeller [2]. When the conventional method is used to draw the axle projection map, the main parameters of the impeller are not optimized and further screened. Of course, for the main design parameters of optimization, Xu and Yuan introduced the application of new optimization techniques such as multi-objective optimization design, genetic algorithm and neural network in the optimization design of impeller, and pointed out the problems that should be paid attention to in the optimization design. [3–4], but genetic algorithms and neural network methods need to build a huge database, which also results in a large workload. For the three-dimensional model of the impeller, Zhang, Huang, Yuan et al [5], The performance of small flow centrifugal pump was simulated by computational fluid dynamics method. Taking low specific speed centrifugal pump as an example, the impeller and volute runners of model centrifugal pump were numerically calculated by ANSYS CFX 14.5 software. [6–8]. In addition, Wang, Shi, Jiang et al selected four parameters, such as blade exit width, impeller exit diameter, number of blades, and blade exit angle, each factor took 3 levels, based on orthogonal test and numerical calculation. Optimize the impeller [9]. In this paper, the orthogonal projection experiment is used to optimize the axial projection of the impeller, and more parameter factors and horizontal factors are selected. And foreign A. Goto [10–11] combines CFD technology with reverse design to optimize the flow structure within the pump cavity through three-dimensional flow field analysis. Jose, Shulka and others studied the relationship between turbulence model, meshing technology and internal flow characteristics and external characteristics, and obtained the results of the experiment through experimental verification [12]. For the first time, Wahba et al introduced the genetic algorithm into the optimization design of centrifugal pump blades and achieved the desired effect [13].

This paper takes the Q5H26 electro-hydraulic circulation pump as the research object, and shows the
electro-hydraulic circulation pump with the flow rate of $5m^3/h$ and the head size of 26 m. Under this research object, the orthogonal design experiment method is used to establish an orthogonal experimental table to select the theoretical optimal parameter matching.

At the same time, after using the orthogonal experimental method to optimize the impeller parameters, the optimized impeller axial projection and the cross-sectional area of the cross-section and the flow center line (F-L) can be drawn by MATLAB, and the axial plane drawn by the traditional method. The projected image and its cross-sectional area of the cross-section are compared with the flow-line midline (F-L) diagram to reflect the rationality of using this method.

The advantage of orthogonal test method is that when three or more impeller variation factors are analyzed, there may be interaction between the factors. Orthogonal experiment can eliminate the interference between factors, and can achieve a large number of comprehensive tests with the least number of tests, effectively and quickly select the best combination of impeller parameters.

2. Drawing of traditional axial projection

After the dimensions of the various parts of the impeller are determined, the axial projection of the impeller can be drawn. The shape of the axial projection map should be modified repeatedly to achieve smooth and smooth. General method steps:

1. Add a circle in a straight line, respectively as the front and rear cover profiles
2. Make a set of inscribed circles that are tangent to the front and rear covers, and make the center line of the inner circle as the center line of the inscribed circle, as shown in figure 1.

![Figure 1. Formation of the middle line of the flow channel.](image1)

3. After drawing the axial projection, check the cross-section change of the flow passage, as shown in figure 2. In the figure, make the inscribed circle of the two flow lines, and the cutting point is A, B. Connect AB to the center of the circle O into a triangle AOB. The high OD of the triangle is equally divided into OE, EC, and CD. A curve AEB passing through point E and perpendicular to the axial flow line is a line forming a cross section of the water. Its length is b. The center of gravity of the line forming the cross section of water is approximately the same as the center of gravity of the triangle AOB (point C), and the radius of the center of gravity is R_c. Since the cross-section of the axial flow through the water must be perpendicular to the flow line of the axial surface, the liquid flows out from the periphery of the impeller, so the cross-section of the flow of the axial flow is a paraboloid formed by the formation of the cross-section of the cross-section as a busbar around the axis. The calculation formula for the area of the cross section of the axial flow can be obtained as follows:

$$\text{Area} = \pi R_c^2$$
\[ b = \frac{2}{3}(s + p) \]  
\[ F = 2\pi R_b b \]  

(1) 

(2) 

Where \( s \) is the length of the inscribed circular chord \( AB \) and \( p \) is the radius of the inscribed circle. 

4. By judging the smoothness of the cross-sectional area of the cross-section and the flow-line midline (F-L), the curve should be a straight or smooth line. 

The known design parameters of the centrifugal pump research object selected in this paper are shown in table 1 below:

| Design parameters of Q5H26 electro-hydraulic circulation pump. |  |
|---|---|---|---|---|---|
| Imported diameter \( D \text{ in (mm)} \) | Outlet diameter \( D \text{ out (mm)} \) | Flow \( Q \text{ (m}^3 / \text{h}) \) | Head \( H \text{ (m)} \) | Rotating speed \( n \text{ (r / min)} \) | Medium density \( \rho \text{ (Kg / m}^3 \) |
| 24 | 22 | 5 | 26 | 7000 | 1200 |

Figure 3. Basic structure of the axial projection of the impeller. 

Figure 4. Cross-sectional area of water and flow line (F-L). 

Through the design variables of the above Q5H26 electro-hydraulic circulation pump, the theoretical formula and the empirical coefficient can be used to calculate the impeller outlet diameter \( D_2 = 62 \text{ mm} \), the impeller outlet width \( b_2 = 4 \text{ mm} \), the impeller inlet diameter \( D_j = 24 \text{ mm} \), and the impeller structure size \( L_4 = 16 \text{ mm} \). The radius \( R_1 \) of the impeller front cover profile arc segment BC is \( R_1 = 5 \text{ mm} \), the radius of the impeller front cover profile arc segment CD \( R_2 = 40 \text{ mm} \), and the impeller front cover profile line exit straight segment DE and the vertical angle \( \alpha_1 = 6^\circ \), the radius of the arc of the impeller rear cover profile line GH is \( R_3 = 16 \text{ mm} \), the angle between the straight line segment GF of the impeller rear cover profile line and the vertical angle \( \alpha_2 = 0^\circ \), the vertical distance from the diameter of the impeller exit to the end point D of the outlet straight line \( L_2 = 4 \text{ mm} \). After determining the values of all the above design variables, the structure diagram of the impeller axis projection map can be determined. The basic structure of the axial projection of the impeller is shown in figure 3; At this time, the change of the cross-surface flow path over the water surface should be checked, and the relationship between
the cross-sectional area of the cross-section and the center line of the flow path (F-L) and the axial projection view at this time can be programmed (figure 4).

As can be seen from the above figure, the image between the area of the cross section and the midline of the channel (F-L) is basically a smooth curve. The results show that the inspection of flow passage section is qualified and meets the basic working conditions of impeller. By the traditional drawing method of axial projection graph, the impeller parameters obtained above are regarded as the final target value, while the optimal combination of these factors is neglected.

The advantage of the orthogonal experimental method is that when the main variation factors of the impeller are analyzed in three or more, and there may be interaction between the factors, the orthogonal experimental method can be used to optimize the impeller parameters and find the impeller parameters. The optimal solution is to optimize the overall axial projection of the impeller.

3. Orthogonal experimental design

3.1. Level factors
The radius \( R_1 \) of the arc section BC of the impeller front cover type line (value range: \( 0.8D_2 \leq R_1 \leq 0.14D_1 \)), and because \( D_2 = 62 \) mm, that is, 4.96 mm \( \leq R_1 \leq 8.86 \) mm. The radius \( R_b \) of the circular arc segment CD of the front plate of the impeller (value range: \( 0.6D_2 \leq R_b \leq 1.2D_2 \)), the same reason, 37.2 mm \( \leq R_b \leq 74.4 \) mm. The range of the angle between the DE and the vertical of the straight section of the impeller front cover profile line is \( 5^\circ \leq \alpha_1 \leq 8^\circ \). The radius \( R_3 \) of the arc segment GH of the impeller rear cover profile line (value range: \( L_1 - 0.5b_2 \leq R_3 \leq L_1 + 0.5b_2 \)), since the values of \( L_1 \) and \( b_2 \) are known, that is, \( 14^\circ \leq 20^\circ \leq 18 \) mm. The impeller rear cover profile line exit straight section GF and the vertical angle \( \alpha_2 \) (value range: \( -3^\circ \leq \alpha_2 \leq 5^\circ \)). The vertical distance \( L_2 \) of the impeller exit diameter to the end point D of the outlet straight line (\( 0.06D_2 \leq L_2 \leq 0.12D_2 \)), that is, 3.72 mm \( \leq L_2 \leq 7.44 \).

The above-mentioned several parameters are paintings that directly affect the axial surface diagram of the impeller, but in order to make the established orthogonal experimental table not too cumbersome and increase the difficulty of calculation, the impeller rear cover type line exit straight line segment can be made. The angle between GF and the vertical \( \alpha_2 = 0 \). Thus, the variation factor is determined as five factors of \( R_1, R_2, \alpha_1, R_b \) and \( L_2 \).

3.2. factor level
The state in which the factor is located is called the factor level. In short, it is the constraint condition corresponding to the design variable in the nonlinear programming. When selecting the factor level, the factor level is generally 2~5. To ensure optimization the accuracy of the results and the ease of calculation. The number of factors determining the factor is 4.

3.3. Evaluation indicators
The evaluation index is also used to evaluate the merits of the orthogonal experiment results. The evaluation index can be multiple or one. In this experiment, an evaluation index is selected. The evaluation method is as follows:

According to the known design parameters of the centrifugal pump described above, the flow line center length \( L \) and the over flow area corresponding to the three points a, c near the inlet and outlet of the impeller and the point b of about half the length of the middle line of the flow path can be used. F, and establish a quadratic curve equation for F-L, which is used as a fitting target curve. Define the curve equation as: \( F_{\text{m}} = f(L) = al^2 + bl + c \). Through MATLAB programming calculation, calculate the length of the centerline of the flow path at the three points a, b, c above, \( L_a, L_b, L_c \) and the value of the over-current cross-sectional area of these three points \( F_a, F_b, F_c \), will The F and L values calculated at these three points serve as three coordinate points for establishing the above curve equation.
When $L_a=1.5$ mm, the overflow area at a can be calculated by MATLAB: $F_a = 530 \text{ mm}^2$
When $L_b=15$ mm, the overflow area at b can be calculated by MATLAB: $F_b = 690 \text{ mm}^2$
When $L_c=28$ mm, the c-flow cross-sectional area can also be calculated as $778 \text{ mm}^2$.

Therefore, the relationship between the three functions of a, b, and c can be established as (1.5, 530), (15, 690) and (28, 778), and the curve equation is solved by the three-point coordinates, so the established the curve equation is as follows:

$$F_{pi} = f(L_i) = -0.2L_i^2 + 15L_i + 509$$  \hspace{1cm} (3)

And because the area of the cross section of the flow of the axial flow of the impeller is calculated as:

$$F_i = 2\pi R_i b_i$$  \hspace{1cm} (4)

Then the values solved by the above two companies are obtained to obtain $\Delta F$, and it can be calculated:

$$\Delta F = \sqrt{\sum_{i=1}^{n} (F_i - F_{pi})^2} \hspace{1cm} (i=1, 2, \cdots, n)$$  \hspace{1cm} (5)

In the above formula, it is the evaluation index of the orthogonal experimental results of the impeller flow path profile.

When continuously adjusting the above five horizontal change factors of $R_1, R_2, \alpha_1, R_3$ and $L_2$, draw a plurality of random point images and curve equation $F_{pi}$ images of the overflow area $F_i$ and L through MATLAB. The degree of fit on the two images can be visually seen in the image. When the value of $\Delta F$ is small, the random point image composed between the over-current cross-sectional area $F_i$ and L will be closer to the image of the curve equation. The more obvious the degree of fitting, the more ideal the impeller runner profile will be. In the process of calculation, in order to simplify the calculation process, a lambda value can generally be preset. In this test, $\lambda = 65$. That is, when the calculated $\Delta F$ value is less than $\lambda$, the entire calculation can be terminated without the need to establish an orthogonal experiment again. That is, $R_1, R_2, \alpha_1, R_3$ and $L_2$ corresponding to the time can be used as the final impeller design parameters.

3.4. Orthogonal experiment table type
Since the above variables have been determined as $R_1, R_2, \alpha_1, R_3$ and $L_2$. For the calculation of the simple and reasonable selection of the horizontal factor of 4, the orthogonal experimental table can be selected as $L_{46} (4^5)$.

4. Orthogonal experimental calculation analysis

4.1. Establishment of the factor level table
In the establishment of the orthogonal experimental table, since the range of the various variation factors and the number of horizontal numbers have been discussed above in this paper, a factor and its factor level table can be preset to perform the initial value of the first orthogonal experiment. The preset factors and their factor levels are shown in table 2 below:

4.2. Orthogonal experiment visual analysis table establishment
By writing a calculation program, calculate the value of the corresponding evaluation index $\Delta F$ under each group of different change factors, select the item with the smallest $\Delta F$ value, and subdivide the five
change factors corresponding to the minimum $\Delta F$, and re-establish the new horizontal factor table and the orthogonal experimental visual analysis table, the first orthogonal experiment visual analysis of the calculation table, as shown in Table 3 below:

### Table 2. Factors and their factors level table.

| Factor | First | The second | The third | The fourth | The fifth |
|--------|-------|------------|-----------|------------|-----------|
| content | $R_1$ | $R_2$ | $R_3$ | $\alpha_1$ | $L_2$ |
| Level   | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 |
| Numerical value | 5,6,7,8 | 40,50,60,70 | 14,15,16,17 | 5,6,7,8 | 4,5,6,7 |

### Table 3. Orthogonal experiment visual analysis calculation table.

| Experiment number | Factor 1 $R_1$ | Factor 2 $R_2$ | Factor 3 $R_3$ | Factor 4 $\alpha_1$ | Factor 5 $L_2$ | Evaluation index $\Delta F$ |
|-------------------|---------------|---------------|---------------|-------------------|---------------|----------------------|
| 1                 | 5             | 40            | 14            | 5                 | 4             | $\Delta F_1$=187.95 |
| 2                 | 5             | 50            | 15            | 6                 | 5             | $\Delta F_2$=128.13 |
| 3                 | 5             | 60            | 16            | 7                 | 6             | $\Delta F_3$=126.01 |
| 4                 | 5             | 70            | 17            | 8                 | 7             | $\Delta F_4$=160.67 |
| 5                 | 6             | 40            | 15            | 7                 | 7             | $\Delta F_5$=141.99 |
| 6                 | 6             | 50            | 14            | 8                 | 6             | $\Delta F_6$=229.88 |
| 7                 | 6             | 60            | 17            | 5                 | 5             | $\Delta F_7$=78.77  |
| 8                 | 6             | 70            | 16            | 6                 | 4             | $\Delta F_8$=99.95  |
| 9                 | 7             | 40            | 16            | 8                 | 5             | $\Delta F_9$=287.21 |
| 10                | 7             | 50            | 17            | 7                 | 4             | $\Delta F_{10}$=206.17 |
| 11                | 7             | 60            | 14            | 6                 | 7             | $\Delta F_{11}$=97.36 |
| 12                | 7             | 70            | 15            | 5                 | 6             | $\Delta F_{12}$=96.99 |
| 13                | 8             | 40            | 17            | 6                 | 6             | $\Delta F_{13}$=104.18 |
| 14                | 8             | 50            | 16            | 5                 | 7             | $\Delta F_{14}$=107.70 |
| 15                | 8             | 60            | 15            | 8                 | 4             | $\Delta F_{15}$=276.59 |
| 16                | 8             | 70            | 14            | 7                 | 5             | $\Delta F_{16}$=183.99 |

It can be seen intuitively from the above table, when $R_1=6$ mm, $R_2=60$ mm, $R_3=17$ mm, $\alpha_1=5^\circ$, $L_2=5$ mm, at this time, it is the minimum value of $\Delta F$. Indicated that the five variables at this time are optimal, and $\Delta F=78.77$, at which point this value is greater than $\lambda=65$.

Therefore, the five variables will be further refined on the basis of this interval, and a second level factor table will be established to continue the calculation. As shown in Table 4 below:

### Table 4. Factor and its factors level table.

| Factor | First | The second | The third | The fourth | The fifth |
|--------|-------|------------|-----------|------------|-----------|
| content | $R_1$ | $R_2$ | $R_3$ | $\alpha_1$ | $L_2$ |
| Level   | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 |
| Numerical value | 6,2,6,4,6,6,6,8 | 61,63,66,69 | 15,3,15,7,16,5,16,8 | 5,1,3,5,5,5,7 | 5,4,5,8,6,4,6,8 |

Through the same method as above, it is found in the second orthogonal experiment that when $R_1=6.6$ mm, $R_2=61$ mm, $R_3=16.5$ mm, $\alpha_1=5.7^\circ$, $L_2=5.8$ mm, This time $\Delta F$ takes the minimum value, ie $\Delta F=63.54$, that is, the value of $\Delta F$ at this time is smaller than $\lambda=65$. That is, the calculation can be stopped, and the horizontal change factor corresponding to this time is taken as the optimal solution.

### 5. Case comparison analysis

The design parameters of the pump are known, so the centrifugal pump design calculation formula is used to obtain each structural size in the axial projection structure, and then the axial projection is drawn
and the axial flow is checked through the water surface. This is to use the traditional design calculation method to design the axial projection of the impeller. The design parameters of the axial projection structure calculated by the calculation formula are shown in Table 5 below.

| Table 5. The main parameters of the impeller under the traditional axial projection drawing. |
|-----------------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| D2 (mm) | b2 (mm) | D1 (mm) | L1 (mm) | R1 (mm) | R2 (mm) | R3 (mm) | α1 (°) | α2 (°) | L2 (mm) |
|---------|---------|---------|---------|----------|----------|----------|--------|--------|---------|
| 62      | 4       | 24      | 16      | 5        | 40       | 16       | 6      | 0      | 4       |

While the above has been discussed, the optimal solution for the five varying factors of the impeller has been obtained by orthogonal experiment. Also by sorting out the following table 6.

| Table 6. Main parameters of the impeller after optimization by orthogonal experiment. |
|-----------------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| D2 (mm) | b2 (mm) | D1 (mm) | L1 (mm) | R1 (mm) | R2 (mm) | R3 (mm) | α1 (°) | α2 (°) | L2 (mm) |
|---------|---------|---------|---------|----------|----------|----------|--------|--------|---------|
| 62      | 4       | 24      | 16      | 6.6      | 61       | 16.5     | 5.7    | 0      | 4       |

Thus, when different impeller parameters are obtained under two different methods, an image of the degree of fitting of the plurality of discrete points composed of the overflow area \( F_i \) and the length of the center line of the flow path to the curve equation \( F_{pi} \) can be drawn separately.

That is, \( \Delta F = 225.98 \) can be calculated, which is the main parameters of the impeller determined by the conventional method of drawing the axial projection. The image of the F-L can be plotted as figure 5; the optimal solution for the main parameters of the impeller after two orthogonal experiments, at this time \( \Delta F = 63.54 \). Can draw the image as figure 6.

It can be clearly seen from the comparison between figures 5 and 6 above that figure 6 is better than the figure 5 in the fitting of the plurality of random points composed of the over-current area \( F \) and the length of the flow line center line \( L \). Many, and when the main parameters of the impeller determined by the traditional method of drawing the axial plane, \( \Delta F = 225.98 \), which is much larger than the \( \Delta F \) calculated by the main parameters of the impeller determined by the orthogonal experimental method. ie \( \Delta F = 225.98 \gg 63.54 \). It is further proved that through the orthogonal experimental design method, while selecting reasonable level change factors, the purpose of optimizing the change factors is also
achieved. Each of the five level change factors has an accuracy of 0.1. At the same time, the preset requirement of $\Delta F = 225.98 < \lambda = 65$ is also satisfied. The corresponding horizontal factor at this time can be taken as the last optimal solution of the impeller design variation parameter. At the same time, under the condition of the optimal solution, the optimized cross-section of the axial flow passage can also be drawn. As shown in figure 7 below:

![Figure 7. Cross-sectional area of the water and the flow line (F-L).](image)

At this time, the relationship between the cross-sectional area of the water passage and the center line (F-L) of the flow passage can be compared with the cross-sectional area of the flow passage and the center line of the flow passage when the main parameters of the impeller are determined by the conventional axial projection drawing method. F-L) The relationship diagram 4 is contrasted. It can be seen that the F-L curve in figure 7 is smoother than that in figure 4, and there is no large undulation, which can be approximated to a straight line. Once again, it can be reflected that the orthogonal experimental method is used to correct the variation of the cross section of the flow passage by adjusting and optimizing the main parameters of the impeller to optimize the axial projection of the impeller of the cross section.

6. Summary
In this paper, through the orthogonal experiment method, the reasonable combination of the five horizontal factors is selected, and the flow path profile inside the impeller is also optimized. At the same time, when the main parameters of the impeller are determined by the conventional method of drawing the axial plane projection, Can calculate $\Delta F = 225.98$, After the optimal solution of the main parameters of the impeller determined by the orthogonal experimental method, the above calculation has been calculated $\Delta F = 63.54$, which is $\Delta F = 225.98 > 63.54$.

It can be shown that the flow path profile inside the impeller is also optimized, so that the axial projection shape of the impeller is improved very well, to the greatest extent. The main design parameters of the impeller and the axial projection of the impeller are optimized.

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