Research of factors influencing centrifugal pump external characteristics based on orthogonal test

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Abstract. In order to investigate the impact on external characteristics of single-stage and single-suction centrifugal pump, four parameters: cutwater gap(δ), blade number(z), impeller outlet width(b) and blade outlet angle(β) were taken into account. Orthogonal test method is a method which can make a comprehensive comparison among factors we are interested in. Thereby, it can't be more appropriate to adopt this approach to study the influence of the four factors referred above. Based on the prototype pump's geometric parameters, each of these factors took four levels. According to the principle of selecting orthogonal array, the L16(4^5) array was selected and 16 models were designed. After that, commercial CFD software CFX was used to calculate the head and efficiency under different conditions to determine the optimal operating condition \(Q_r\). The 16 models' rated flow rates were basically smaller than the prototype's. Considering this difference, in order to analyze the influence on the head under similar condition, the flow rate was made dimensionless and 3 conditions are chosen(\(Q_r/Q=1, 1.25\) and \(1.375\)). Through the analysis of averaged respond head and efficiency, the laws of head and efficiency changing with the variation of the factors were obtained. Commonly, if a dependent's change cause by a independent variable is smaller than 5%, we can neglect the independent variable's effect. Thus the paper presents a research showing the factors' changing limitations considering the head changing by a percentage smaller than 5%. The conclusion of this article has important reference value for design of centrifugal pumps.

1. Introduction

As the key component of pump, impeller's geometric parameters have significant influence on pump's performance. Therefore, researchers conducted a series of studies about this. With the rapid development of computer technology, computational fluid dynamics (CFD) is gradually maturing as a numerical method. It's more and more widely used in the fluid machinery such as pumps, turbines and...
fans. Pump performance prediction based on CFD has basically reached the level of engineering application [1].

Liu [2] did the flow analysis by means of CFD and found that the head of the model pumps increase with the increase of blade number. Luo [3] used RNG k-ε and VOF cavitation model to analyze the performance of a boiler feed pump and found that impeller inlet geometry has important influence on performance improvement. While both papers are focus on only one factor that affects pump's performance, we can't make sure whether one factor's influence is larger than the others'. In this paper, in order to synthetically investigate the impact on external characteristics of single-stage and single-suction centrifugal pump, four parameters: cutwater gap (δ), blade number (z), impeller outlet width (b) and blade outlet angle (β) were taken into account. The orthogonal test method was used as the basement of this study and CFD calculations were done to get the head and efficiency of the pump. The impacts of various factors were compared, and the factors' changing limitations considering the head changing smaller than 5% was got.

2. Orthogonal test design
The whole orthogonal test design was based on a prototype single-stage and single-suction centrifugal pump made by Gruppo ATURIA. The main parameters are listed below: rated flow rate \( Q_R = 194.44 \text{ kg/s} \), rated head \( H = 50 \text{ m} \), rated rotational speed \( n = 1480 \text{ r/min} \), blade number \( z = 7 \), impeller diameter \( D = 409 \text{ mm} \), cutwater gap \( \delta = 36 \text{ mm} \), impeller outlet width \( b = 41 \text{ mm} \), blade outlet angle \( \beta = 30^\circ \).

Table 1. Orthogonal test project

| test model | blade number (z) | cutwater gap (δ) (mm) | impeller outlet width (b) (mm) | blade outlet angle (β) (°) |
|------------|------------------|------------------------|-------------------------------|--------------------------|
| 1          | 5                | 36                     | 41                            | 21                       |
| 2          | 7                | 50.4                   | 41                            | 29.4                     |
| 3          | 8                | 57.6                   | 41                            | 33.6                     |
| 4          | 6                | 43.2                   | 41                            | 25.2                     |
| 5          | 6                | 57.6                   | 28                            | 21                       |
| 6          | 8                | 50.4                   | 32.8                          | 21                       |
| 7          | 7                | 43.2                   | 24.6                          | 21                       |
| 8          | 5                | 57.6                   | 24.6                          | 29.4                     |
| 9          | 8                | 36                     | 24.6                          | 25.2                     |
| 10         | 5                | 50.4                   | 28                            | 25.2                     |
| 11         | 6                | 50.4                   | 24.6                          | 33.6                     |
| 12         | 6                | 36                     | 32.8                          | 29.4                     |
| 13         | 7                | 36                     | 28                            | 33.6                     |
| 14         | 7                | 57.6                   | 32.8                          | 25.2                     |
| 15         | 8                | 43.2                   | 28                            | 29.4                     |
| 16         | 5                | 50.4                   | 32.8                          | 33.6                     |

According to the orthogonal test method, the four parameters: \( \delta \), \( z \), \( b \) and \( \beta \) are considered to chose 4 levels, so the orthogonal table \(L_{16}(4^2)\) is chosen as shown in Table 1.

3. Numerical method

3.1. Mesh generation
The 3D models of impeller and volute were produced by professional software Unigraphics NX, the gap between impeller and volute was appended to impeller. The impeller inlet and volute outlet were
extended properly to reduce the effect of boundary conditions on inner flow. Relativity examination of grid number was done and the selected grid number was about 140,0000. Figure 1 shows the Mesh of the whole passage and the tongue part.

![Mesh of the whole passage and the tongue part](image)

**Figure 1.** Mesh of the whole passage and the tongue part

3.2. Boundary conditions

CFX 12.1 was used to simulate the inner flow field. The SST(Shear Stress Transport) turbulence model was applied. The simulation was steady and moving reference frame was applied considering the impeller-volute interaction. Convergence precision of residuals is $10^{-4}$. According to the results got from Park Sang Hyun [4] and Spence R [5], mass flow rate inlet and pressure outlet were selected as inlet and outlet boundary conditions respectively. The static pressure was set at outlet, the value was 0.

4. Results and discussions

4.1. Optimal flow rate

Parameters' changes will inevitably lead to changes in head and efficiency. For the 16 models, the rated flow rate is tend to move from the original one. Commonly, if a dependent's change cause by a independent variable is smaller than 5%, we can neglect the independent variable's effect. Several flow rates were calculated to determine the rated flow, the final results are shown in Table 2 with the 5% deviation considered. For the purpose of comparing the performance of models under similar condition, the relative flow rate ($Q/Q_R$) was used. 3 conditions were chosen, $Q/Q_R=1, 1.25$ and $1.375$.

| model | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    | 14    | 15    | 16    |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $Q_R$ (kg/s) | 165   | 146   | 156   | 166   | 117   | 146   | 146   | 107   | 156   | 136   | 136   | 165   | 166   | 146   | 156   | 156   |

4.2. Response averages
One aspect of the orthogonal test method utilises response averages, calculated for each specific geometry parameter variable, to provide detail relating to the influence of the geometric factors on the head and efficiency. For example, to calculate the response average of head relating to $z=5$, the average of the head would be calculated from arrangements 1, 8, 10 and 16. These response averages are shown in Figure 2 and Figure 3.

**Figure 2.** Response averaged heads
Due to the discrete geometry changes, the graphs are simply drawn with straight lines. The lines are generally tend to be either rising or declining along with the increasing of the factors except the outlet angle's ($\beta$) which have 2 inflection points. It should also be noticed that, as for cutwater gap ($\delta$), the averaged heads have a obvious drop at $\delta=43.2$.

4.3. Recommended change of the factors
As referred to above, the influence can be ignored when smaller than 5%. In practice, we modify the geometric parameters to guarantee the expected performance such as smaller pressure pulsations. We hope that the change of the parameters can effectively reduce the pressure pulsations and retain the external characteristics simultaneously. Thus, the change of external characteristics should limited to less than 5%. Comparing the two Figures, Figure 3 and Figure 4, it's clearly shown that factor's influence on the head is larger, so the change of the head should be limited rather than the efficiency.

According to the discrete geometry changes, it's assumed that the relationship is linear between 2 levels, then the change of the head according to the geometry changes can be evaluated. Table 3 shows the estimated maximum allowable variation of geometric parameters in each range. The 4 levels are divided into 3 ranges from small to large, that's to say, range 1 represents 5~6 for $z$ while range 3 represents 7~8.

| variable | 1 | 2 | 3 |
|----------|---|---|---|
| $\Delta z$ | 1 | 1 | 1 |
| $\Delta \delta$ (mm) | 4.2 | 3.2 | 3.5 | 5.7 | 4.9 | 7.2 | 5.9 | 6.8 | 5.2 |
| $\Delta b$ (mm) | 2.1 | 1 | 0.6 | 6 | 4.1 | 2 | 7 | 2.7 | 1.5 |
| $\Delta \beta$ (°) | 4.2 | 4.2 | 2 | 4.2 | 3.4 | 1.9 | 4.2 | 4.2 | 4.2 | 4.2 |
5. Conclusions
A numerical model of an entire single-stage single-suction centrifugal pump has been used to conduct a parametric study covering 4 main geometric parameters. The parameters include the cutwater gap, blade number, impeller outlet width and blade outlet angle with 4 different configurations being used for each parameter. The numerical results of the prototype were compared with the experimental data and showed good agreement.

An L₁₆(4⁵) has been successfully constructed. The analysis of the array identify how the head and efficiency change with the variance of geometric parameters. Based on the previous work, an estimation was done to provide a reference value of allowable variation of geometric parameters, which can be helpful to the modification of the rotor or volute.

This article is preparing for further work which focusing on the influence on pressure pulsations caused by the 4 geometric parameters.

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