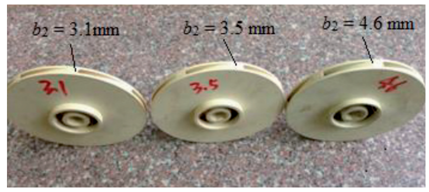
Influencing factors of self-priming time of multistage self-priming centrifugal pump



Factores que influyen en el tiempo de autocebado de una bomba centrífuga autoaspirante multietapa

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RESUMEN

- Las bombas centrífugas autocebantes son un tipo de equipo para drenaje y riego aplicado en irrigación de cultivos, paisajismo urbano, eliminación y refrigeración de polvo y suministro de agua a edificios. En la actualidad, las bombas centrífugas autoaspirantes de una etapa dominan el mercado de bombas. Por lo que la cuota de mercado de las bombas autoaspirantes multietapa, que pueden proporcionar líquido a más alta presión, es considerada rara vez adecuada. El tiempo de autocebado es un parámetro importante que mide el rendimiento en esa etapa de las bombas centrífugas autocebantes multietapa. Aunque muchos estudios se han centrado en las influencias de un solo factor en el tiempo de autocebado de las bombas centrífugas autocebantes de una etapa, sólo unos pocos han discutido el tiempo de autocebado de las bombas autocebantes de varias etapas. En el presente trabajo, realizamos un estudio experimental que combinó ensayos ortogonales (tipo Taguchi) y análisis correlación "gris" (Grey Relational Analysis - GRA) del tiempo de autocebado para investigar los factores que influyen en ese tiempo de autocebado de una bomba centrífuga autocebante multietapa y acortar el tiempo de autocebado correspondiente. El ancho de salida del álabe del impulsor, el espacio radial entre el impulsor y el difusor, el área del orificio de reflujo y el número de etapas de la bomba centrífuga autocebante multietapa fueron seleccionados como factores que influyen en la prueba ortogonal. Se realizó este análisis ortogonal del tiempo de autocebado de la bomba centrífuga autocebante multietapa y los resultados se utilizaron como base para obtener el orden de importancia de todos los factores de influencia a través de un análisis correlación "gris" (Grey Relational Analysis - GRA). Los resultados demuestran que el tiempo de autocebado aumenta gradualmente con un aumento en el ancho de salida del álabe del impulsor, pero que disminuye continuamente con un aumento en el número de etapas y el área del agujero de reflujo. A medida que aumenta la separación radial, aumenta el tiempo de autocebado y luego disminuye. En resumen, el área del agujero de reflujo es el factor de influencia más importante del tiempo de autocebado de la bomba centrífuga autocebante multietapa, seguido por el ancho de salida de la pala del impulsor, el espacio radial y el número de etapa. Estos resultados proporcionan referencias importantes para acortar el tiempo de autocebado de las bombas centrífugas autocebantes multietapa.
- **Palabras clave:** Bomba centrífuga autocebante multietapa, Análisis de correlación "gris", Ensayos ortogonales, Ensayo de relación de tiempo de autocebado.

ABSTRACT

Self-priming centrifugal pump are a type of drainage and irrigation equipment applied in crop irrigation, urban landscaping, dust prevention and cooling, and building water supply. At present, single-stage self-priming centrifugal pumps dominate the pump market. Hence, the market share for multistage self-priming pumps, which can provide high-pressure liquid, is barely adequate. Self-priming time is an important parameter that measures the self-priming performance of multistage self-priming centrifugal pumps. Although many studies have focused on the influences of a single factor on the self-priming time of single-stage self-priming centrifugal pumps, only a few have discussed the self-priming time of multistage self-priming pumps. In the current work, we conducted an experimental study that combined the orthogonal, grey relational, and self-priming time tests to investigate the influencing factors of the self-priming time of a multistage self-priming centrifugal pump and shorten the corresponding self-priming time. The outlet width of the impeller blade, the radial gap between the impeller and the diffuser, the area of backflow hole, and the number of stages of the multistage self-priming centrifugal pump were selected as the influencing factors in the orthogonal test. The orthogonal analysis of the self-priming time of the multistage self-priming centrifugal pump was conducted, and the results were used as the basis in obtaining the order of importance of all influencing factors through the grey relational test. Results demonstrate that self-priming time increases gradually with an increase in impeller blade outlet width but that it decreases continuously with an increase in stage number and area of backflow hole. As radial gap increases, self-priming time increases and then decreases. In summary, the area of backflow hole is the most important influencing factor of self-priming time of the multistage self-priming centrifugal pump, followed by impeller blade outlet width, radial gap, and stage number. These findings provide important references for shortening the self-priming time of multistage self-priming centrifugal pumps.

Keywords: Multistage self-priming pump, Grey relational test, Orthogonal test, Self-priming time.

1. INTRODUCTION

Pumps are a type of general machine with many varieties and extensive applications, and they are used in all places with liquid flow [1-3]. Statistics indicate [4,5] that pumps' energy consumption accounts for nearly 22% of the world's energy used by electric motors. Self-priming centrifugal pumps, or self-priming pumps, have no bottom valve in the inlet pipe. The pump structure is changed such that it can store some water after stopping. The water returns to the appropriate position in the pump via the backflow channel, and the above process is repeated, thereby realizing self-priming. The process requires water supply only at the initial stage; no water supply is necessary in subsequent start-ups. After a short operating period, the pump itself can suck up the water and be put into normal operation. A self-priming pump is easy to operate and has stronger adaptability than an ordinary centrifugal pump. Such pump is extremely suitable for situations with frequent start-ups or difficult liquid irrigations [6-8]. Multistage self-priming centrifugal pump is developed on the basis of a single-stage self-priming centrifugal pump [9-12]. Self-priming performance is an important parameter to evaluate the performance of self-priming pumps, and it determines whether the water under the pump can go into the pump. According to the Chinese standard JB/T6664-2007, the self-priming time of a 5 m vertical pipe should be controlled within 100 s. Given that the self-priming process of self-priming pumps is a complicated, unsteady gas–liquid flow phenomenon, studying the self-priming performance of pumps is difficult. Moreover, many challenges emerge in the study of the influencing factors of the self-priming time of self-priming pumps.

On the basis of known challenges, some studies about the influences of geometric factors of self-priming pumps on self-priming time have been reported in academia [13-18]. However, most studies focused on the influences of single-factor changes on self-priming time, and few of them discussed the primary and secondary order of influencing factors. Given that the concept of a multistage self-priming pump is relatively new, the effect of the stage number of multistage self-priming pumps on self-priming time remains unknown. Thus, studying the influence of the geometric factors of multistage self-priming pumps on self-priming time and determining the order of importance of all influencing factors is a problem that requires immediate solutions. In the current study, a new multistage self-priming centrifugal pump was designed, and the influence of impeller blade outlet width, radial gap between impeller and diffuser, area of backflow hole, and stage number on the self-priming time of the pump was deeply explored. The order of importance of different influencing factors was also obtained. The research results are expected to provide some references for shortening the self-priming time of multistage self-priming centrifugal pumps.

2. STATE OF THE ART

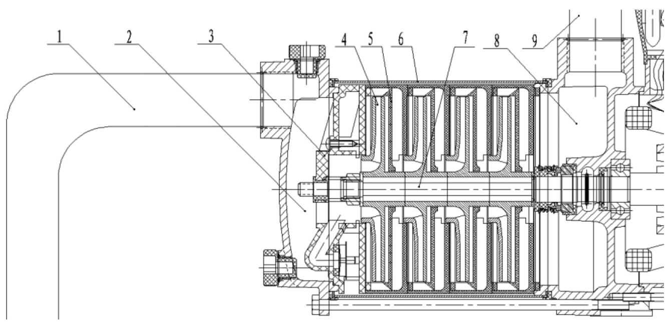
Some studies on the self-priming time of self-priming centrifugal pumps have been conducted by theoretical calculation, numerical calculation, and test measurement. Using theoretical calculations, Zhao et al. [19] deduced the formulas of self-priming time and exhausting rate according to fluid mechanics, thermodynamics, air dynamic equation, and energy invariant equation cited on studies of vertical self-priming centrifugal pumps. However, relevant research results are only applicable to single-stage vertical self-priming centrifugal pumps. Fan et al. [20] deduced the calculation formula of the self-priming time of an external-mixture self-priming centrifugal pump on the basis of the thermodynamic equation of ideal air and the compressible ideal one-dimensional unsteady flow equation. However, high-efficiency self-priming centrifugal pumps in the market mainly use the internal-mixture structure. Yi [21] summarized the data about self-priming time and specific speed of 31 modes of external-mixture self-priming centrifugal pumps and explored the corresponding rules and trends. However, the self-priming time gained from the relevant calculation formula had a great range and only had statistical significance. Although the proposed theoretical calculation of self-priming time is not highly accurate and has narrow applicability, the theoretical calculation process indicates that moving bubbles are the relevant results of main media accomplished by self-priming. Using numerical calculation, Wang et al.[22] adopted an inlet void fraction of 15% for the self-priming process of rotational flow of a self-priming pump using Fluent software. They found that the liquid phase drove the gas phase flow by phase interaction during the self-priming process and finally obtained the self-priming time. Li et al. [23,24] simulated the gas–liquid states in a pump at different moments (initial, middle, and late stages) of the self-priming process by using the quasi-steady method with decreased void fraction and then estimated the time needed for the entire self-priming process. However, such a quasi-steady method is greatly different from the real self-priming process. For the numerical calculation of the self-priming time of self-priming pumps, scholars hypothesized that either the inlet void fraction of a pump comprised several fixed numerical values (5%, 10%, and 15%) and the velocity inlet was set or gas filled the entire pump inlet and the gas inlet velocity was a mean value. The former hypothesis was not based on the self-priming numerical calculation of self-priming pumps but on the numerical simulation of ordinary gas–liquid flow pumps. The latter hypothesis was close to the real self-priming situation, but it assumes that the velocity inlet was an average, which obviously contradicted the inversely V-shaped variation of self-priming speed in the self-priming process. The study of Huang et al. [25] was the closest to the real simulation of the self-priming time of a single-stage self-priming pump because they did not set the velocity inlet or mass outlet in the simulation process. However, the relevant calculation model only hypothesized that the self-priming height was 0.25 m. This result was inconsistent with the vertical self-priming height of 3 or 5 m in the real self-priming process, thereby failing to reflect the flow rule of the whole self-priming process. With regard to experimental measurements, existing studies mainly focused on the influences of structural improvement [26-28], volume of fluid reservoir [29], area and position of backflow hole [30], and tongue gap [31] of self-priming pumps on self-priming time. However, relevant studies only emphasized the influences of a single factor on the self-priming time of self-priming pumps.

Existing theoretical calculations on the self-priming time of self-priming pumps are mainly performed at the theoretical hypothesis level, whereas numerical calculations emphasize the analysis of the internal flow field in gas–liquid flow pumps. Few numerical studies focused on the real self-priming process of self-priming pumps, and experimental studies emphasized the influences of a single factor on self-priming time. Moreover, research data on the self-priming time of multistage self-priming pumps have yet to be reported due to the lack of multistage self-priming pumps in the market. Thus, the influencing factors of the self-priming time of a multistage self-priming centrifugal pump were discussed in the current work through the combination of an orthogonal test and grey relational test. The results are expected to provide reliable references for achieving optimal performance for multistage self-priming centrifugal pumps. The remainder of this paper is organized as follows. Section 2 describes the structure of the new multistage self-priming centrifugal pump and introduces the detailed design of the orthogonal and grey relational tests. Section 3 discusses the influencing rule of main factors in relation to the self-priming time of multistage centrifugal pumps. Section 4 summarizes the paper and provides relevant conclusions.

3. METHODOLOGY

3.1. STRUCTURAL DESIGN OF MULTISTAGE SELF-PRIMING CENTRIFUGAL PUMP

In this study, a motor direct connection mode in the self-priming pump was used with a compact structure and easy installation and operation. The entire pump was composed of inlet and outlet pipes, gas–liquid mixture cavity, self-priming cover plate, impeller, diffuser, outer casing, shaft, gas–liquid separation cavity, and a motor, among others (Figure 1). The largest innovation point in this model was the design of a new self-priming backflow device with high self-priming performance. Based on a radial diffuser, the device was composed of a gas–liquid separation cavity, outer casing, self-priming cover plate, and gas–liquid mixture cavity. In the self-priming process, the high-pressure water in the final-stage pump section flowed into the first-stage pump section through the backflow device to obtain the gas–water mixture again. After the self-priming process, the backflow valve in the self-priming cover plate was closed automatically under a large pressure difference, thereby effectively increasing the pump efficiency. This multistage self-priming pump had good self-priming performance, and the pump efficiency was as high as that of conventional centrifugal pumps. Moreover, the core components of centrifugal pumps includes the impeller and diffuser, whose geometric parameters are calculated by using the velocity coefficient method, which is shown in Table I.



1. Inlet pipe; 2. gas–liquid mixture cavity; 3. self-priming cover plate; 4. impeller; 5. diffuser; 6. outer casing; 7. shaft; 8. gas–liquid separation cavity; 9. outlet pipe
Fig. 1: Assembly diagram of a multistage self-priming centrifugal pump

Geometric parameter	Value	Geometric parameter	Value
Inlet diameter of the impeller D_1 (mm)	20	Outlet width of the impeller b_2 (mm)	3
Hub diameter of the impeller D_{hb} (mm)	33.5	Number of the outward diffuser blades Z_p	9
Outlet diameter of the impeller D_2 (mm)	108	Number of the return diffuser blades Z_n	9
Inlet angle of the impeller blade β_1 (°)	40	Inlet diameter of the outward diffuser D_3 (mm)	109
Outlet angle of the impeller blade β_2 (°)	15	Inlet angle of the outward diffuser α_3 (°)	5
Wrap angle of the impeller blade θ_w (°)	150	Outlet angle of the return diffuser α_6 (°)	50
Number of the impeller blades Z	8	Rotational speed n (r/min)	2800

Table I: Basic geometrical parameters

3.2. ORTHOGONAL TEST DESIGN

The orthogonal test is a scientific method that arranges and analyzes a multifactor test. In the orthogonal test, the experimental program and experimental results are arranged, tested, and analyzed scientifically by using the standardized orthogonal table following the mathematical orthogonal principle. The test aims to find a mathematical method for optimizing or relatively optimizing production conditions and technological conditions. This study mainly investigated the self-priming time (T_p) needed for the 5 m self-priming height of a multistage self-priming centrifugal pump. The program of minimum self-priming time (T_{min}) was then proposed.

According to previous studies, the major geometric factors that affect the self-priming time of self-priming centrifugal pumps include impeller blade outlet width (b_2), radial gap between impeller and diffuser (δ), and area of backflow hole (S). Given that the multistage self-priming centrifugal pump was selected as the

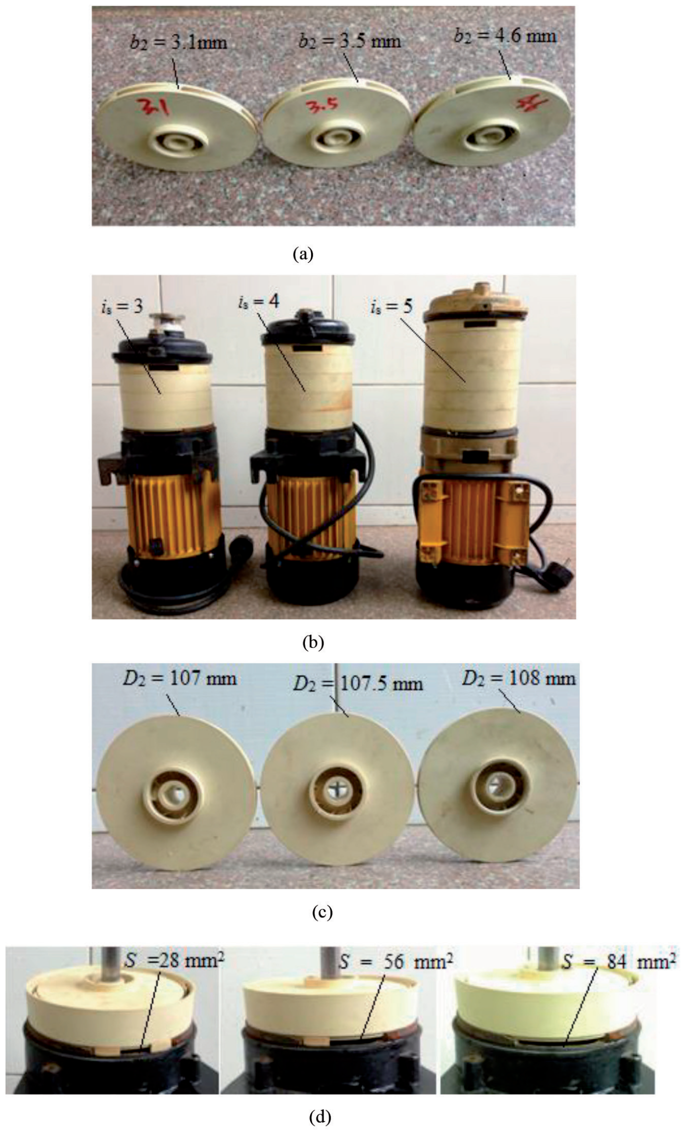


Fig. 2: Models with different test factors. (a) Different impeller outlet widths. (b) Different stage numbers. (c) Different impeller diameters. (d) Different backflow holes

Level	A b_2(mm)	B i_s	C δ (mm)	D S (mm²)
1	3.1	5	0.5	28
2	3.5	4	0.75	56
3	4.6	3	1	84

Table II: Factor levels

research object, stage number (i_s) was important in realizing self-priming performance. Therefore, these four parameters were selected as test factors. The base diameter of the outward diffuser was 109 mm. δ was realized by cutting the impeller, and *S* was achieved by blocking the backflow hole.

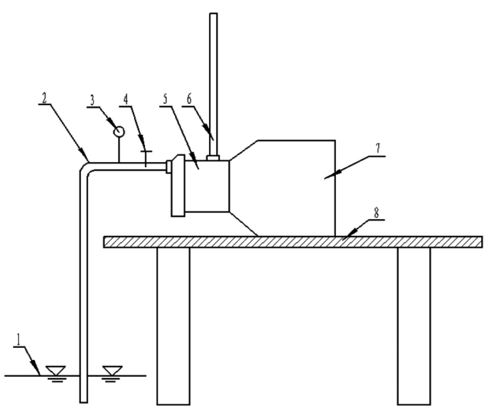
On the basis of an existing initial pump model, three levels were selected for each test factor, as shown in Table II. During the impeller processing, b_2 may develop a certain deviation. The theoretical values of impeller outlet width should be 3 and 4.5 mm, but the measured values in this study were 3.1 and 4.6 mm. The physical models of four different test factors under three levels in Table I are shown in Figure 2.

Test schemes were designed following the orthogonal list by the "horizontal seating by number" (Table III). One vertical row in the table indicated that a test was needed. For instance, the four test factors in the #1 experiment were b_2 = 3.1 mm, i_s = 5, δ = 0.5 mm, and *S* = 28 mm².

No.	1	2	3	4	5	6	7	8	9
A	3.1	3.1	3.1	3.5	3.5	3.5	4.6	4.6	4.6
B	5	4	3	5	4	3	5	4	3
C	0.5	0.75	1	0.75	1	0.5	1	0.5	0.75
D	28	56	84	84	28	56	56	84	28

Table III: Test schemes

In order to verify the credibility of self-priming tests of self-priming pumps, a self-priming experiment was made based on the self-priming pump testbed in Jiangsu University to measure the self-priming time during the self-priming process. As shown in Figure 3, an iron elbow and a ball valve are installed at the pump inlet. The vertical height of the inlet elbow above the water surface is 5 m, while a plastic pipe with the height of 2 m is installed at the pump outlet. All nine groups of models were sent to a company for processing. To reduce the test error, we repeated each group of tests thrice.



1. Pool; 2. inlet elbow; 3. vacuum gauge; 4. ball valve; 5. self-priming pump; 6. outlet pipe; 7. Motor; 8. Platform
Fig. 3: Experimental setup of the self-priming test

3.3. GREY RELATIONAL TEST DESIGN

Although an orthogonal test can study the influences of different factors on self-priming time via the range analysis in a certain horizontal range, the range analysis results are influenced by the levels of selected factors. Given that these factors have different dimensions, the order of importance of influencing factors determined with the orthogonal test is not completely accurate. Considering the grey system (incomplete information system) between self-priming time and influencing factors, the order of importance of the influencing factors of self-priming time was obtained accurately with a grey relational test.

The number sequence that reflects system behaviors is called the reference number sequence. The number sequence that comprises factors that affect system behaviors is called a comparison number sequence. The reference number sequence (mother sequence) was set as

$$Y = \left\{ Y(i) \middle| i = 1, 2, \cdots, N \right\} \tag{1}$$

The comparison number sequence (subsequence) was set as

$$X_j = \left\{ X_j(i) \middle| i = 1, 2, \cdots, N; j = 1, 2, \cdots, M \right\} \tag{2}$$

where *X* is the comparison number sequence, *Y* is the reference number sequence, *M* is the number of comparison number sequences, *N* is the number of reference number sequences, *i* is the variable of the reference number sequence, and *j* is the variable of the comparison number sequence.

The relationship between the reference number sequence and the comparison number sequence can be generally divided into three types following their own attributes, namely, benefit, cost, and interval types. The benefit type refers to the positive relation between the reference number sequence and the comparison number sequence. The cost type refers to the negative relation between the reference number sequence and the comparison number sequence. The interval type implies that the reference number sequence improves as the comparison number sequence approaches a fixed region. Dimensionless data processing must follow the basic principle in which the order of importance of the number sequences remains the same before and after the dimensionless processing. This situation meets the isotonicity condition. For the benefit type and cost type, we use

$$Z_{ij} = (Y_{ij} - \min_i Y_{ij}) / (\max_i Y_{ij} - \min_i Y_{ij}),\ j \in J_1 \tag{3}$$

$$Z_{ij} = (\max_i Y_{ij} - Y_{ij}) / (\max_i Y_{ij} - \min_i Y_{ij}),\ j \in J_2 \tag{4}$$

For the interval type, we use

$$Z_{ij} = \begin{cases} 1 - (q_1^j - Y_{ij}) / \max\left\{ q_1^j - \min_i Y_{ij}, \max_i Y_{ij} - q_2^j \right\}, Y_{ij} < q_1^j \\ 1, Y_{ij} \in [q_1^j, q_2^j] \\ 1 - (Y_{ij} - q_2^j) / \max\left\{ q_1^j - \min_i Y_{ij}, \max_i Y_{ij} - q_2^j \right\}, Y_{ij} > q_2^j \end{cases}, j \in J_3 \tag{5}$$

where Y_{ij} is the value of the comparison number sequence *j* in the reference number sequence *i*. Z_{ij} is the value of Y_{ij} after dimensionless processing. J_1 is the subscript set of benefit type. J_2 is the subscript set of cost type. J_3 is the subscript set of interval type. *q* is the interval variable.

The relational degree is actually the difference degree of the geometric shape between curves. Therefore, the different sizes between curves can be used as the measurement scale of relational degree. The relational coefficient between the reference number sequence *Y(i)* and the comparison number sequence $X_j(i)$ is as follows:

$$\zeta_j(i) = \frac{\min_j \min_i \left| Y(i) - X_j(i) \right| + \kappa \max_j \max_i \left| Y(i) - X_j(i) \right|}{\left| Y(i) - X_j(i) \right| + \kappa \max_j \max_i \left| Y(i) - X_j(i) \right|} \tag{6}$$

where ζ is the relational coefficient and κ is the resolution ratio. The smaller κ indicates a higher resolution. The value interval of κ is (0, 1), and 0.5 is generally selected as the value of κ.

4. RESULT ANALYSIS AND DISCUSSION

4.1. ORTHOGONAL TEST RESULTS OF SELF-PRIMING TIME

The self-priming time needed for a 5 m self-priming height was T_p, as shown in Table IV. The data calculation process of the orthogonal test was introduced as follows.

For T_p, the first column was

$$K_{1A} = 60 + 61.3 + 75 = 196.3\ \text{s}$$
$$K_{2A} = 45.7 + 69 + 122 = 236.7\ \text{s}$$
$$K_{3A} = 58 + 80 + 191.3 = 329.3\ \text{s}$$

where K_{1A}, K_{2A}, and K_{3A} are the sums of self-priming time when A is at levels 1, 2, and 3, respectively. To compare the performances at different A levels, k was introduced as follows.

$$k_{1A} = 196.3/3 = 65.4\ \text{s}$$
$$k_{2A} = 236.7/3 = 78.9\ \text{s}$$
$$k_{3A} = 329.3/3 = 109.8\ \text{s}$$

where K_{1A}, K_{2A}, and K_{3A} are the mean self-priming times under the corresponding levels of A. K_B, K_c, and K_D and K_B, K_c, and K_D in the remaining three columns were calculated by the same method used in the first column. The calculated results are shown in Table V. The range difference R was the maximum among K_{1A}, K_{2A}, and K_{3A} in all columns subtracting the minimum. The first column was used as an example as follow:

$$R_A = \max\{k_{1A}, k_{2A}, k_{3A}\} - \min\{k_{1A}, k_{2A}, k_{3A}\} = 44.4\ \text{s}.$$

Generally, range differences reflect the effects of different factors in the test. A high range difference demonstrates that the change in range difference in the test range greatly affects the indexes; the difference is an important factor. The range difference in Table IV presented that the order of importance of all influencing factors was $B > A > D > C$, as shown in Table VI (see section: supplementary material). The range difference analysis preliminarily revealed that the stage number of the multistage self-priming pump is the most important factor that affects self-priming time, whereas the influence of radial gap can be overlooked. In shortening the self-priming time, the stage number of the multistage self-priming pump should not be excessively large. However, there are some possible inaccuracy of the above results due to that the range difference results in the orthogonal test being influenced by the levels of selected factors.

No.	1	2	3	4	5	6	7	8	9
T_1 (s)	59	60	76	45	70	122	58	80	177
T_2(s)	59	62	75	46	70	122	58	80	197
T_3(s)	62	62	74	46	67	122	58	80	200
T_p (s)	60	61.3	75	45.7	69	122	58	80	191.3

Table IV: Experimental results of self-priming time

No.	K_1 (s)	K_2(s)	K_3 (s)	K_1 (s)	K_2 (s)	K_3 (s)	R (s)
A	196.3	236.7	329.3	65.4	78.9	109.8	44.4
B	163.7	210.3	388.3	54.6	70.1	129.4	74.8
C	262	298.3	202	87.3	99.4	67.3	32.1
D	320.3	241.3	200.7	106.8	80.4	66.9	39.9

Table V: Range difference analysis of self-priming time

As shown in Figure 4 (see section: supplementary material), the trend intuitive diagram of test indexes and test factors can be obtained by using the influencing factors as the x-axis and the mean self-priming time T_p as the y-axis. The test indexes change with the test factors. Given the increase in b_2, T_p increased gradually. Certain scholars argued that the increase in b_2 would strengthen the air-exhausting capacity of the self-priming pump, thereby shortening the self-priming time. The conclusions derived in the current work contradict those of relevant scholars because the relevant conclusions of previous scholars were based on three preconditions, namely, adequately large fluid reservoir, adequately large gas–liquid separation cavity, and adequately large backflow hole. However, the gas–liquid separation cavity and the initial area of the backflow hole in this model pump were calculated from small flow parameters. In the orthogonal test, the continuous increase of b_2 reflected the continued growth of flow rate, and the backflow hole could not facilitate a sufficient return of liquid from the gas–liquid separation cavity to the gas–liquid mixture cavity. Finally, the increase of b_2 weakened the gas exhausting capacity of the self-priming pump. The above reason also explains why T_p decreased with the increase of S. Moreover, T_p was negatively correlated with i_s mainly because more pump stages increased the pressure in the gas–liquid separation cavity. This condition not only facilitated the speed of gas–liquid separation but also increased the pressure difference at two ends of the backflow channel. Consequently, the backwater capacity of the self-priming pump was enhanced. Additionally, T_p increased first and decreased with the increase of δ, thereby indicating that the relationship between δ and T_p was not positive. In the majority of the cases, the value of δ ranged from 0.5 mm to 2 mm. When δ >2 mm, the self-priming performance declined gradually.

For single factor A, the order of importance for self-priming time was A_1 A_2 A_3. For single factor B, the order of importance for self-priming time was B_3 B_2 B_1. For single factor C, the order of importance was C_3 C_1 C_2. For single factor D, the order of importance was D_3 D_2 D_1. In summary, the combined factors of the minimum self-priming time were B_3 A_1 D_3 C_2, that is, the self-priming performance of the multistage self-priming centrifugal pump was optimal. The minimum self-priming time was 40 s from a self-priming test, thereby indicating that the influencing factors of the self-priming time of the multistage self-priming pump can form an optimal combination and greatly shorten the self-priming time.

4.2. ANALYSIS OF SELF-PRIMING TIME BASED ON GREY RELATIONAL TEST RESULTS

The reference number and comparison number sequences can be obtained from Tables III and IV. The results are shown in Table VII (see section: supplementary material). T_p was used as the reference number sequence, whereas b_2, i_s, δ, and S were used as the comparison number sequences.

As shown in Figure 4, *T-A* is the benefit-type functional relationship, *T-B* and *T-D* are the cost-type functional relationships, and *T-C* is the interval-type functional relationship. Given that the self-priming time is shorter and the self-priming performance of the self-priming pump is better, T itself was used as the cost type number sequence in this study. The dimensionless processing of benefit-, cost-, and interval-type number sequences was conducted with Eqs. (3), (4), and (5), respectively. The results are listed in Table VIII (see section: supplementary material).

By substituting the values in Table VIII into Eq. (6), the relational coefficients of each number sequence were obtained. The results are shown in Table IX (see section: supplementary material). Therefore, the order of importance of the four influencing factors of the self-priming time of the multistage self-priming centrifugal pump is as follows:

area of backflow hole $S >$ impeller blade outlet width of the $b_2 >$ radial gap $\delta >$ stage number i_s.

This result is markedly different from that in Table V, and the order of the most important factors was even opposite, thereby fully proving that the order of importance of influencing factors in the range difference analysis of the orthogonal test was inaccurate. This inaccuracy was mainly due to the range difference results in the orthogonal test being influenced by the levels of selected factors. Furthermore, the area of the backflow hole and the backwater quantity were the key factors that determined the self-priming time, which needed to be accurately calculated. The stage number of the multistage self-priming pump could be freely selected as a secondary factor on the basis of user needs.

5. CONCLUSION

To study the influences of the geometric factors of multistage self-priming centrifugal pumps on self-priming time and greatly shorten the self-priming time, a new multistage self-priming centrifugal pump was designed. The experimental study on shortening the self-priming time was conducted by combining the orthogonal test, grey relational test, and self-priming time test. Some conclusions are as follows.

(1) Self-priming time is positively correlated with the impeller blade outlet width, and it is negatively correlated with the stage number and area of backflow hole. The time is positively correlated with the radial gap in the beginning and then results in a negative relation.

(2) The backwater is the carrier of gas movement, so the area of backflow hole mostly influences the self-priming time, thereby indicating that the key of self-priming lies in backwater quantity. Stage number slightly influences the self-priming time, thereby indicating that it is not the key influencing factor of self-priming time.

(3) The influencing factors of the self-priming time of multistage self-priming centrifugal pumps are correlated and restricted mutually. They can form an optimal combination to shorten the self-priming time of these pumps.

This paper discusses in depth the relationship between the geometric factors of the multistage self-priming pump and self-priming time by combining the orthogonal test and grey relational test. A new multistage self-priming centrifugal pump with excellent self-priming performance was designed successfully. However, numerical simulation of the self-priming time of the pump has not been conducted, that is, only an experimental study was done. Future studies could predict the self-priming time of multistage self-priming pumps accurately by performing numerical calculations.

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SUPPLEMENTARY MATERIAL

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