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Optimal Design Schemes of Centrifugal Pump Compound Impeller at Super-Low Specific Speed

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The paper has established sixteen design schemes for super-low specific speed centrifugal pump compound impeller with orthogonal method, based on the main factors impacting the design of compound impeller, like short blades number of compound impeller, the relative position of blade radial inlet, blade circumferential bias degree, deflection angle, etc.,. By numerical simulation, the optimal design scheme has been determined. Compared with the method of permutation and combination, the optimal design scheme can greatly reduce the workload of the designers. In the meantime, by applying the orthogonal method for compound impeller design, the compound impeller internal pressure and velocity field distribution become quite reasonable, the curve H–Q is more flat, the $\eta-Q$ curve excurses to the big flow, and also the work performance is fairly good.

1. Introduction

Recently, lots of works have been done to improve the performance of super-low specific speed centrifugal pump compound impeller(ns≤30),and the results show that compound impeller with matched long and short blades can effectively prevent the emergence and development of wake flow, thus improving the velocity distribution in the impeller. With finite blade correction coefficient increased, the pump lift will be improved, one of the effective ways to enhance the performance of low specific speed centrifugal pump(CUI Baoling et al. (2006), Majidi K. (2005), Kergourlay G et al. (2007), Yuan Shouqi et al.(2007), Yuan Shouqi(1997)). With compound impellers consisting of long and short blades being able to take many forms, the different setting places of long and short blades will produce different design effects, and will also impact the efficiency of the compound impeller. Based on the analysis of the short blade bias degree, the factors influencing the compound impeller short blade bias design have been provided in Ref. (Zhang Jinfeng (2007)). And in Ref.(CHEN Song-shan et al. (2005), Yuan Shouqi et al. (2008)), orthogonal method is used to calculate and analyze the performance of different short blades by selecting three factors , three levels $L_9(3^3)$, three factors , and four levels $L_9(3^4)$. Although certain valuable results of compound impeller have been achieved in recent years, the design of high-speed low specific speed centrifugal pump is still deficient, with maximum flow design, area ratio principle design, non-overload design, etc., adopted to design super-low specific speed centrifugal pump in general. According to the main factors influencing the compound impeller design, this paper presents a method of using the orthogonal method and numerical simulation method to select a high performance super-low specific speed centrifugal pump compound impeller among numerous design models.(Francesco M, et al. (2008), Hayashi I, Kaneko S,(2014), Spence R, Amaral-Teixeira J. (2009),Spence R, Amaral-Teixeira J.(2008), Yao Zhifeng et al. (2010), Wu Yulin et al. (2012))

2. The functional representation

The main performance parameters of super-low specific speed centrifugal pump are as following: lift: 400, flow: 20, rotation rate: 8300, efficiency, net positive suction head. According to the above design parameters and requirements, based on the design tradition and experiences on super-low specific speed centrifugal pump,

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the long and short blades will be spatial warping blades, equal in number, and placed alternately. According to the documents (Zhang Jin-feng (2007), Zhu Zu-chao (2007)), the basic geometric parameters are preliminarily determined as in table1:

Table 1: the basic geometric parameters of impeller

D_1 / mm	D_2 / mm	β_1 / $(\circ)$	β_2 / $(\circ)$	b_1 / mm	b_2 / mm	S / (mm^2)
60	180	17	39	17.5	4	6×20.82

3. Orthogonal design method

According to orthogonal design principle, the factors and levels that influence the compound impeller design will be selected as following:

(1) Factor (A): short blade number is represented by z ; Level: 3, 4, 5, and 6;

(2) Factor (B): relative position of short blade radial inlet, namely the ratio of the short blade inlet diameter D_i and impeller external diameter D_2 ; Level: 0.55, 0.60, 0.65, and 0.60.

(3) Factor(C): short blade circumferential bias degree t_i/t : t_i means the lattice spacing between short blade working face and the long blade back side; t means the lattice spacing between two long blades; the ratio of the two lattice spacing t_i/t means the circumferential bias degree; Level: 0.50, 0.53, 0.56, 0.53;

(4) Factor (D): deflection angle α ; Level: 0 °3 °, 6 °, and 9 °.

Based on the above factors and levels, and the principle of orthogonal method, as well as $L_{16}(4^4)$ design scheme, sixteen different kinds of compound impeller design schemes have been determined. Table 2 shows experimental factors and levels, and table 3 reflects orthogonal design schemes.

Table 2: Orthogonal experimental factors

Level	Factor A	Factor B	Factor C	Factor D
	Blades No. z	Short blade radial position D_i/D_2	short blade circumferential bias degree t_i/t	deflection angle α
1	3	0.55	0.50	0°
2	4	0.60	0.53	3°
3	5	0.65	0.56	6°
4	6	0.70	0.60	9°

Table 3: Designing schemes

Scheme No.	factors Matched	Scheme No.	factors Matched	Scheme No.	factors Matched	Scheme No.	factors Matched
□	1-1-1-1	□	2-1-2-3	□	3-1-3-4	□	4-1-4-2
□	1-2-2-2	□	2-2-1-4	□	3-2-4-3	□	4-2-3-1
□	1-3-3-3	□	2-3-4-1	□	3-3-1-2	□	4-3-2-4
□	1-4-4-4	□	2-4-3-2	□	3-4-2-1	□	4-4-1-3

4. Numerical simulation and analysis of orthogonal design schemes

4.1 Numerical calculation method

By using FLUENT software, the paper has adopted three-dimensional unsteady incompressible Reynolds $N-S$ equation and standard $\kappa-\varepsilon$ turbulence model to realize the coupling of pressure and velocity with SIMPLEC algorithm. For discrete format, the pressure has applied second-order central difference format. Velocity, turbulent kinetic energy and turbulent kinetic energy coefficient have applied second order upwind difference format. During the iterative calculation, the relaxation iteration has been applied, and the stress relaxation coefficient is 0.3, while the speed is 0.7, turbulent kinetic energy is 0.8, and the turbulent kinetic energy dissipation rate is 0.8.

4.2 Simulation test results of orthogonal method

The above 16 kinds of compound impeller centrifugal pump design schemes have been performed simulating calculation, as shown in figure 1. Lift and efficiency value under each design condition have been obtained, seeing the results in table 4. The lift and efficiency value of compound impeller in scheme (5), (7), (8), namely factor level B-1, orthogonal design scheme with short blades ratio $z = 4$, haven't met the design requirements. The lift of compound impeller in design scheme (9) is higher, while the efficiency value is lower. It's due to unreasonable collocation of long and short blades. The results further prove that not all compound impellers with long and short blades are reasonable, among which there must be impellers with better or poor performances. According to the tests data, lift and efficiency indexes from all other design schemes have satisfied the design requirements. Compared with the design indexes, the lift value and efficiency value have increased at different levels. Lift value has been improved 11.15% and the efficiency value has been enhanced 6.69%.

Table 4: Experimental results at point of Design condition

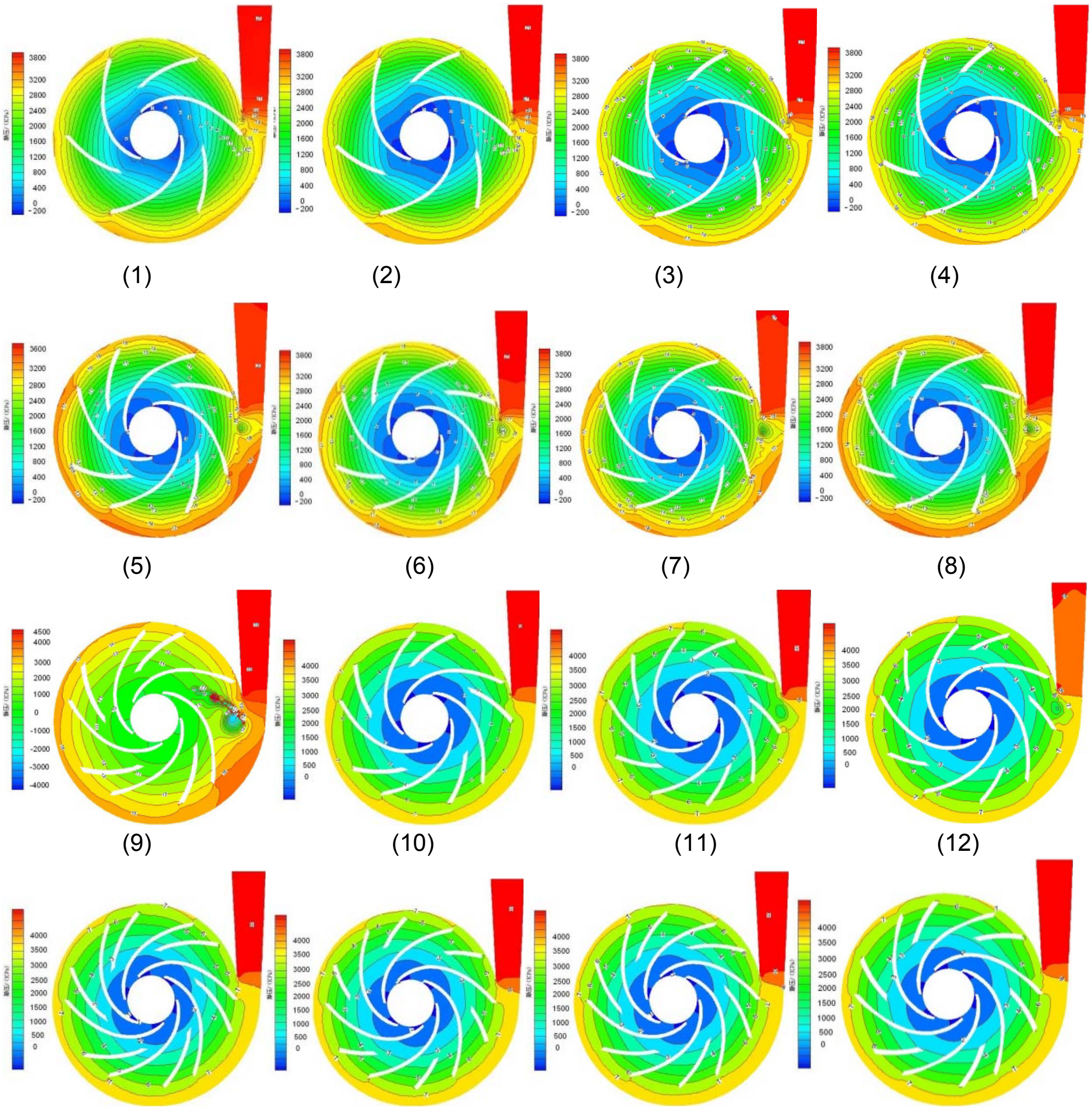
Scheme	H/m	$\eta/\%$	Scheme	H/m	$\eta/\%$	Scheme	H/m	$\eta/\%$	Scheme	H/m	$\eta/\%$
(1)	404.49	67.99	(5)	373.86	59.43	(9)	494.03	65.69	(13)	439.72	69.19
(2)	408.03	68.97	(6)	398.57	66.30	(10)	431.76	68.18	(14)	439.96	67.33
(3)	404.14	67.86	(7)	397.03	64.64	(11)	431.38	65.97	(15)	438.84	69.35
(4)	402.52	68.60	(8)	385.93	61.41	(12)	417.04	65.30	(16)	444.58	69.10

4.3 Range analysis of test results

The test results have been further analysed and processed according to range analysis method, the range value between lift value and efficiency value and short blade orthogonal designing factor level have been obtained. Exactly, K_i means the sum of corresponding level calculation results; $\overline{K_i}$ means the average calculation result of corresponding level; R means the range value, and the results have been shown in table 5. It can be observed from the range value difference R that among short blade design influencing factors: the primary and secondary sequence that influences lift is ACDB. For efficiency value, the affecting primary and secondary order is ABCD

Table 5: Range analysis results at point of Design condition

Level	H				η			
	A	B	C	D	A	B	C	D
K_1	1619.18	1712.10	1679.02	1658.52	273.42	262.3	269.36	265.26
K_2	1555.39	1678.32	1637.77	1665.06	251.78	270.78	263.05	263.05
K_3	1774.21	1671.39	1724.06	1654.34	265.14	267.82	262.29	264.57
K_4	1763.10	1650.07	1732.42	1733.96	274.97	264.41	269.94	269.94
$\overline{K_1}$	404.80	428.03	419.76	414.63	68.36	65.58	67.34	66.32
$\overline{K_2}$	388.85	419.58	409.44	416.27	62.95	67.70	65.76	65.76
$\overline{K_3}$	443.55	417.8475	431.015	413.585	66.285	66.955	65.57	66.14
$\overline{K_4}$	440.78	412.52	433.11	433.49	68.74	66.10	67.49	67.49
R	51.9275	15.5075	23.6625	18.8600	5.7975	2.1200	1.9125	1.7225



(1) (2) (3) (4)

(5) (6) (7) (8)

(9) (10) (11) (12)

Figure 1: Static pressure distribution of different impellers at the point of Design condition

4.4 Analysis of various factors influencing on the short blade design

According to the above range analysis results, the factors changing with the lift and efficiency value are as following:

Factor A: with the increasing of blade number, the lift decreases at first and then gradually increases. The lift value is the lowest when the blades number is 4, and while the blade number is 5, the lift value is the highest. Same as lift value changing trend, the efficiency value is the lowest when the blade number is 4. The efficiency increases along with the increasing of blade number. Taken lift and efficiency value together, the ideal blade number is five.

Factor B: short blade radial inlet locates in the second level, namely taking $D_i \big/ D_2 = 0.60$; the corresponding efficiency reaches the highest. In the first level, taking the value $D_i \big/ D_2 = 0.55$, the lift value is slightly lower than the value in the second level, but the efficiency value is much lower. By comparison, the lift and efficiency values of all other levels are lower, thus, the second level has been selected as the level value of factor B.

Factor C: In addition to the second level $t_i \big/ t = 0.53$, in which the lift value has not met the design requirements, lift indexes of all other levels have reached the design requirements. Efficiency is rising gradually with the increasing of short blade circumferential bias degree and has reached the highest at the fourth level. Therefore, the fourth level has been selected for factor C, namely the short blade circumferential bias degree is $t_i/t = 0.60$.

Factor D: When the deflection angles are 0°, 3° and 6°, which means that the horizontal levels are one, two, and three; lift indexes of pump are similar. When the $\alpha = 9^\circ$, the lift value enhances obviously. Therefore, the fourth level has been chose for factor D, namely the angle of short blade turning to the long blade back side is $\alpha = 9^\circ$.

According to the above factors and levels analysis, the optimal compound impeller design scheme will be as following: the short blade number is preliminary determined as $z = 5$, the relative position of radial inlet is $D_i/D_2 = 0.60$, and the angle of short blade turning to the long blade back side is $\alpha = 9^\circ$.

5. The numerical simulation of conventional impeller and compound impeller

The optimal compound impeller design scheme under orthogonal method has been compared with the conventional impeller with the same number of long blades. Numerical simulation for both types of impellers has also been carried out under the design conditions.

Through numerical simulation, the performance efficiency value of compound impeller is around 68.19%, while the performance efficiency of regular impeller is about 61.25%. As shown from the results, the efficiency of compound impeller was obviously higher than that of the conventional impeller. The static pressure distribution and the relative velocity distribution of both impellers have been shown in figure 1 and figure 2. From the relative velocity distribution figures, it can be concluded that flow separation phenomenon of the long blade back side has been obviously reduced after adding short blades between long blades. And also, backflow phenomenon of two long blades outlet has been reduced. From static pressure figure, it can be seen that comparing with conventional impeller, the high pressure area of compound impeller outlet and laryngeal of the volute have been significantly decreased. The static pressure has distributed more uniformly, and the flow ability is also better than conventional impeller. Moreover, internal static pressure distribution and the relative velocity distribution of compound impeller are superior to the conventional impeller.

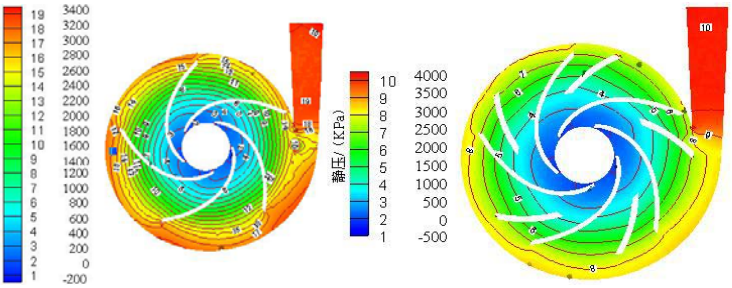


Figure 2: Static pressure distribution of two impellers on design conditions

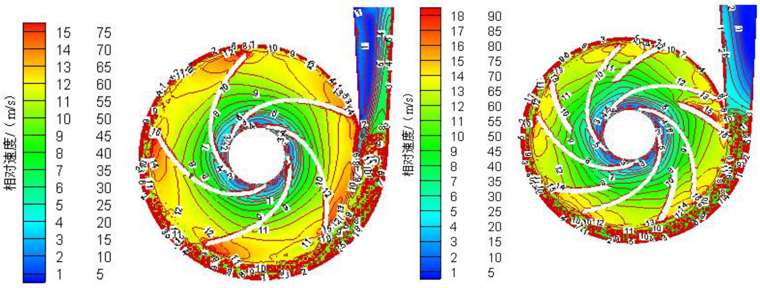


Figure 3: Relative velocity distribution of two impellers on design conditions

6. Conclusion

(1)Among all impeller performance influenced factors, the orthogonal design method has been applied. Under numerical simulation and analysis, the optimal compound impeller design scheme can be obtained, which is also more convenient than the traditional method, permutation and combination, and the workload of the designers will be greatly reduced. Therefore, it can be boiled down that the method is a feasible optimal design method.

(2)Under the same design condition, comparing design scheme applying the orthogonal method with conventional design scheme, the internal pressure field and velocity field distribution of the optimal compound impeller are more reasonable with higher efficiency and better performance, $Q-H$ curve is smoother, and $Q-\eta$ curve excurses to the big flow.

(3)Compound impeller design method is one of effective ways to improve the efficiency of super- low specific speed centrifugal pump. However, if the long and short blades inappropriate combined, the efficiency of the pump will be reduced. Therefore, only in the reasonable collocation of the long and short blades, can the compound impeller design gain the optimal design results.

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