Optimization design for Downhole Turbine Generator Based on Response Surface Method

Huiping Lu, Bo Li, Xiaodong Zhang

***Abstract*—To improve the power generation efficiency, the parameters matching analysis method for the downhole generator with asymmetric turbine is established on basis of the experimental design theory, response surface methodology and orthogonal experimental design. Based on the calculation results by Computational Fluid Dynamics (CFD), the blade parameters of stator and rotor which affect the objective function a lot are screened out by the single-factor experimental design. Then, to get the optimal design results, these parameters are analyzed and determined by the Box-Behnken design and response surface methodology. Once the approximation model of objective function is constructed, the interplay between these parameters is discussed in this paper. Furthermore, the experimental study is conducted on the optimal design point of the new asymmetric turbine. The results show that CFD simulations are in good accordance with the calculations based on response surface method. The relative error of experimental value is smaller compared with the predictive value, and the trends of performance curves are almost the same. What's more, the efficiency of new asymmetric turbine increases by 10% after optimizing matching. It declares that the design method based on Box-Behnken and the orthogonal design experiments can be used in the matching analysis of asymmetric turbine's parameters. The research in this paper provides reliable guidance in turbine blade design and technological parameters optimizing.**

***Index Terms*—asymmetric turbine, response surface methodology, Box-Behnken design, parameters matching, efficiency.**

I. Introduction

Turbine generator can adapt high temperature and high pressure in the downhole environment. It has many advantages in underground power supply, for which using drilling fluid flow to make long-term and persistent electricity. Due to the limitation of the installation size, the spiral blade is often adopted for downhole turbine generator [1, 2]. Scholars and research institutions had discussed the analysis methods and relevant test methods theoretically and experimentally for the turbine [3-6]. XianYong Z. and Jin F. studied the performance difference of three kinds of turbines with the spiral blade, which are uniform-pitch, varying-pitch and the changing-width-blade turbine, respectively. They also studied the turbine with uniform thickness and uniform pitch, and gained the simple theoretical calculation formula. Due to lack of the stator basin calculation model and analysis of the inlet angel of the rotor, the theoretical calculation method is only applicable to the turbine with a single rotor [7-9]. BaoDe J. et al. focused on blades improvement of the turbine, which is the key component of downhole turbine generator [10, 11]. In recent years, some optimization methods have been applied to the design of centrifugal impeller. Ashimara studied the performance of pump impeller by inverse problem method and combining gradient optimal method with exploratory technique [12]. Wahabi W. et al. used multi-objective genetic algorithm and the CFD for optimization of impeller's guide blade [13, 14]. Lei Z. and Chunlin W. et al. carried out optimization design on fire pump and centrifugal impeller blades based on the theory of experimental design and response surface approximate methods [15, 16]. Improvement design of blade profile is more usual in current research, and few studies have examined the interaction of parameters between the stator and rotor. Different matching types of structure parameters will significantly affect the performance of the turbine. Therefore, matching analysis method of structure parameters for the asymmetric turbine, which based on the experimental design, response surface methodology was proposed for the first time. In this paper, the optimal matching combination was obtained. Also the hydraulic efficiency of the turbine was improved without changing or redesigning the blade structure. Then the power generation efficiency of the downhole turbine generator was increased.

II. Downhole Turbine Generator Modeling and Simulation Verification

When the peripheral parts is removed, the structure diagram of downhole mud turbine generator is shown in Fig.1 (a). Turbine is one of the most important parts of downhole turbine generator. This study focuses on the turbine with spiral blades, which is composed of a stator and rotor in Fig.1 (b). The stator acts as a guide roller, which is fixed in front of the turbine, and adjusts the mud flow direction of shocking to blade surface to improve the efficiency. The rotor is the power component. Drilling fluid impacts the turbine blades to produce circumferential force which makes turbine rotate, thus promoting the generator to achieve power generation.

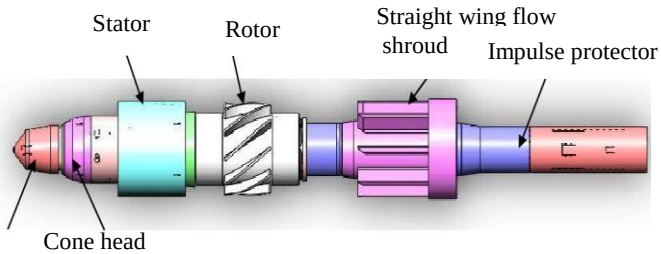


Fig.1. The structure of downhole turbine generator

After modified and improved, the three-dimensional grids of the turbine model embracing the global grid and flow passage grid across the blade were shown in Fig.2. The boundary conditions can be described as follows: the type of interface produced was set as frozen rotor. Because of stationary of the stator and rotation of the rotor when turbine working, the interaction is generated. And for all of the CFD simulations of this paper, it was achieved by specifying a normal speed at the inlet and a total pressure at the outlet. The normal speed was set to 5.1m/s, and the pressure at the outlet was set to 1atm. No-slip walls were specified for the domain walls.

Fig.2 Grid computing model

III. Objective Function Definition

The main function of the turbine in the generator is to convert the hydraulic power into mechanical energy, which is transferred to the generator rotor to achieve power by the shaft. The main performance parameters that determine the properties of turbine include torque, output power, pressure drop and efficiency. When the turbine works under the rated condition, the loss of energy is minimum and the efficiency is maximum. In this paper, the maximum turbine efficiency, which has a linear relation with torque and pressure drop, is selected as the objective function. The objective function is:

$$\eta_{\max} = \frac{P}{P_0} \tag{1}$$

where η_{max} is the maximum efficiency of turbine, P represents the output power described as $P=n\pi M/30$, and M is the torque at maximum efficiency, n is the corresponding rotation speed at maximum efficiency, $P_0=\Delta P\cdot Q$, which is the input power, ΔP is the pressure drop and Q is the flow rate at maximum efficiency.

IV. Single-factor Experiment Design and Parameters Selection

The symmetry turbine is selected as the initial model. β_1, θ_1, Z_1 and m_1 are the parameters of the stator, and β_2, θ_2, Z_2 and m_2 are the parameters of the rotor. The control parameters of initial model are determined by the above theoretical analysis, so the relevant parameters of initial model are set as: $\beta_1=\beta_2=44.71°$, $\theta_1=\theta_2=90°$, $Z_1= Z_2=5$, $m_1=m_2=5$mm. Table 1 shows the schemes arrangement of sensitive analysis based on single-factor design method.

Figs. 3-6 show the comparisons of the performance for sensitive analysis of blade variables. It can be seen that β_1, β_2, Z_1 and Z_2 have a greater impact on the turbine performance at a certain speed range. However, θ_1, θ_2, m_1 and m_2 have little effect on the turbine performance, showing that the value of those four parameters can be chosen in a wide range. When the stator's spiral angle is small, the turbine efficiency is less than the efficiency of the initial turbine. In addition , by increasing the stator blade number, it can make the turbine efficiency close to 60% when the rotation speed is 1200 r/min. The changing of the rotor's spiral angle will have great influence on the turbine efficiency. When the blade number of the rotor increases, the maximum efficiency of the turbine is not improved but reduced instead. So, it is visible that rotor blade number is unfavorable for overmuch. The four significant factors which are β_1, β_2, Z_1, Z_2 respectively, can be obtained. Meanwhile, they will be selected as the objects for the later design and analysis based on response surface method.

Table1. Single-factor experiment design

No.	β_1/(°)	β_2/(°)	Z_1	Z_2	θ_1/(°)	θ_2/(°)	m_1 /mm	m_2 /mm
Tur0	44.71	44.71	5	5	90	90	5	5
Tur1	38	44.71	5	5	90	90	5	5
Tur2	44.71	38	5	5	90	90	5	5
Tur3	44.71	44.71	8	5	90	90	5	5
Tur4	44.71	44.71	5	13	90	90	5	5
Tur5	44.71	44.71	5	5	60	90	5	5
Tur6	44.71	44.71	5	5	90	120	5	5
Tur7	44.71	44.71	5	5	90	90	3	5
Tur8	44.71	44.71	5	5	90	90	5	3

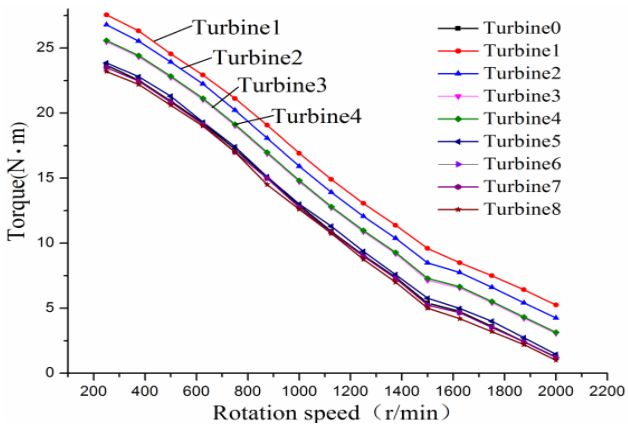


Fig.3 Comparisons of Torque

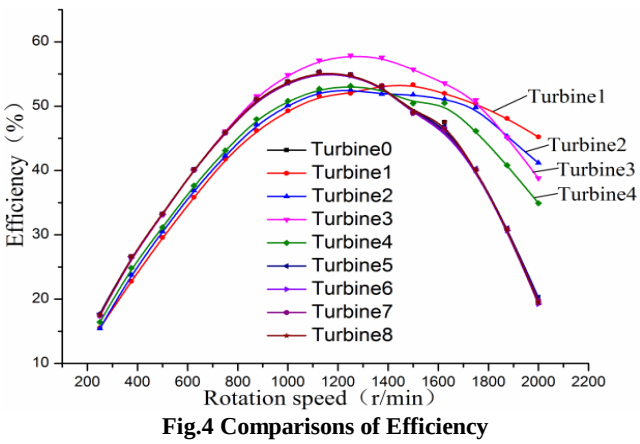


Fig.4 Comparisons of Efficiency

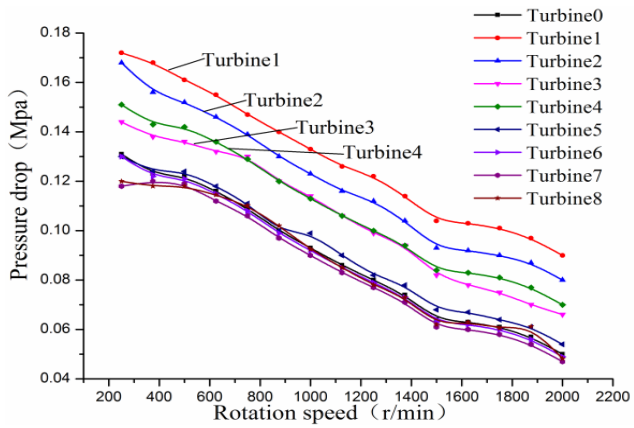


Fig.5 Comparisons of Pressure drop

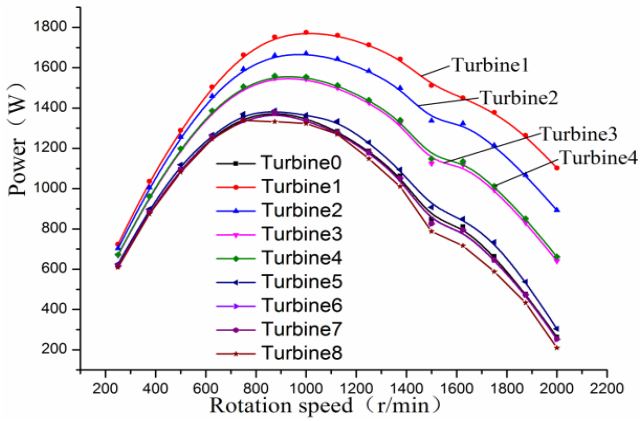


Fig.6 Comparisons of Power

V. BOX-BEHNKEN DESIGN AND THE RESPONSE SURFACE ANALYSIS

In order to conduct the combination design of blades parameter, the Box-Behnken method is adopted. On account of multiple factors of blades and the characteristic of the method, it is chosen four factors and three levels arranged in Table 2. The values of other control parameters are selected from the initial model.

Table 2. Impact factors and level of Box-Behnken method

Factor	Level		
	-1	0	1
β_1/(°)	20	33	46
β_2/(°)	20	33	46
Z_1	5	10	15
Z_2	5	10	15

Table 3. The evaluation precision of response surface

Sample number	R^2	Ra^2	C.V.%
29	0.9929	0.9857	1.91

According to the Box-Behnken design method, 29-group schemes were determined. To calculate the experimental error repeatedly, 24-group schemes were for factorial points and others for the center point. The influence between the objective function and control parameters was obtained by the Design Expert software. The evaluation coefficients of response surface are shown in Table 3. The values of R^2 and R_a^2 are close to 1, indicating that the response surface fitted by experimental sample can be a very good approximation of the real value.

The relationship between the objective function and the blade variable can be expressed through the established mathematical model, namely the response surface regression equation for the significant factors as follows:

$$\begin{aligned} R_1 &= 0.60506 + 1.54740\beta_1 + 2.73339\beta_2 - 3.29251Z_1 \\ &-3.06738Z_2 - 0.00887574\beta_1\beta_2 + 0.049231\beta_1 Z_1 \\ &-0.0055\beta_1 Z_2 - 0.016538\beta_2 Z_1 + 0.030769\beta_2 Z_2 \\ &+0.044 Z_1 Z_2 - 0.016356\beta_1^2 - 0.038250\beta_2^2 \\ &+0.06943 Z_1^2 + 0.065433 Z_2^2 . \end{aligned} \tag{2}$$

In the Fig.7, when the rotor's spiral angle β_2 is at a middle level, the objective function value increases accordingly with the augment of stator's spiral angle β_1. Also the objective function value has a bigger value when β_1 is at the high level. Meanwhile，the objective function is strongly influenced by stator's spiral angle β_1 from Figs. 8-9. When Z_1 and Z_2 take a certain value, the objective function value increases with the augment of β_1. From Fig.8, when β_1 takes the high level, the objective function has a greater value at both ends of the high and low level of Z_1. From Fig.9, when β_1 takes the high level, the objective function has a greater value at a low level of Z_2. From Figs. 10-11, when the rotor's spiral angle β_2 is at the middle level, the objective function value increases gradually along with the augment of the Z_1 and Z_2. In the Fig.12, the objective function decreases with the increasing of Z_1 and Z_2 at the same time.

Optimization variables within the scope of high and low levels in the above Table 2 are obtained by Design Expert. Then the optimization results obtained by response surface method were compared with the simulation results calculated by CFD in the same condition, as shown in Table 4. After the optimization matching, the objective function value is obviously improved. The predicted values of the fitting formula and the CFD calculation values are very close, showing that the response surface method is reliable. Therefore, response surface method can be used for matching analysis of turbine parameters to improve the efficiency of the turbine generator.

Table 4. Optimal parameters and result verification

Preferred parameters				Predicted efficiency/%	Simulation efficiency/%	initial value/%
β_1/°	β_2/°	Z_1	Z_2			
46	29.18	15	5	58.3574%	56.72%	49.06%

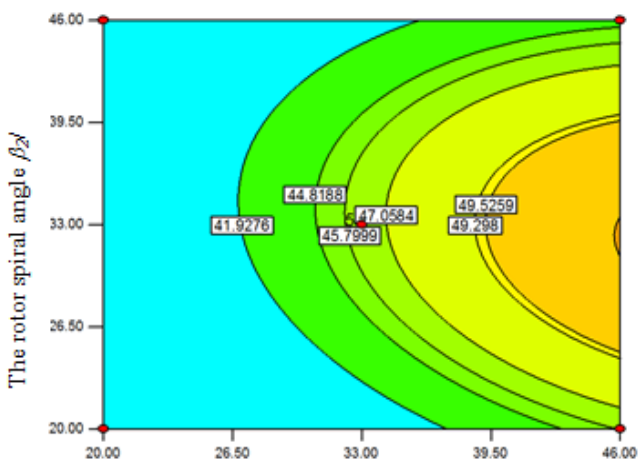


Fig.7 Impact of β_1 and β_2 on efficiency

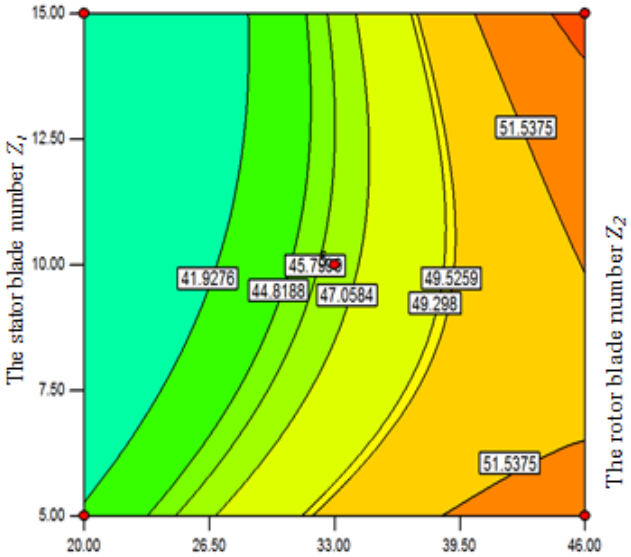


Fig.8 Impact of β_1 and Z_1 on efficiency

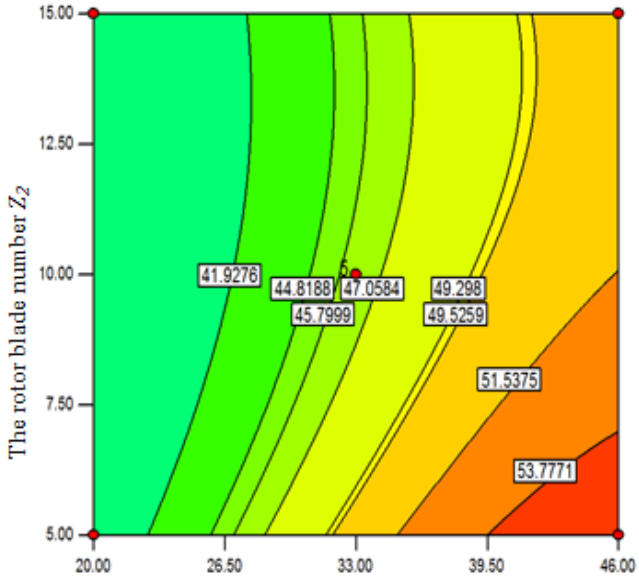


Fig. 9 Impact of β_1 and Z_2 on efficiency

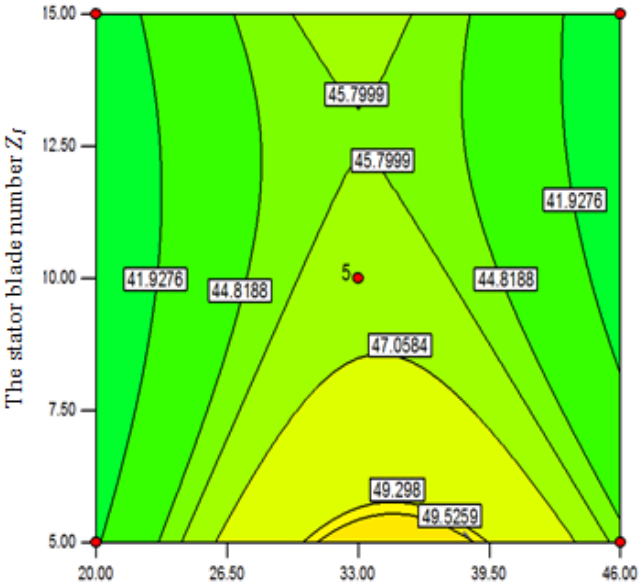


Fig. 10 Impact of β_2 and Z_1 on efficiency

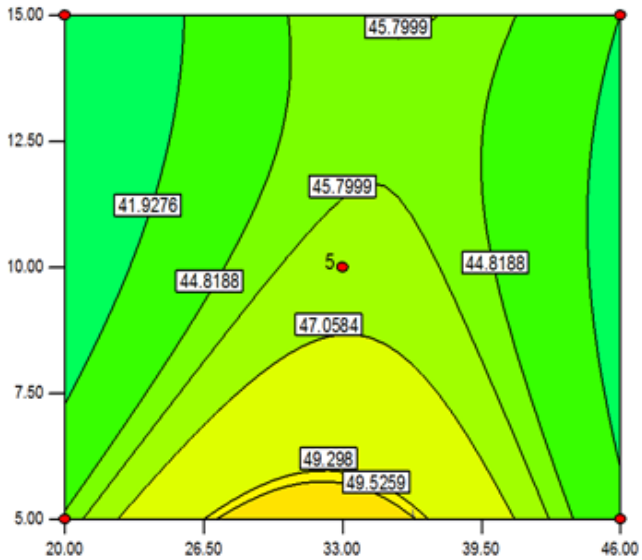


Fig.11 Impact of β_2 and Z_2 on efficiency

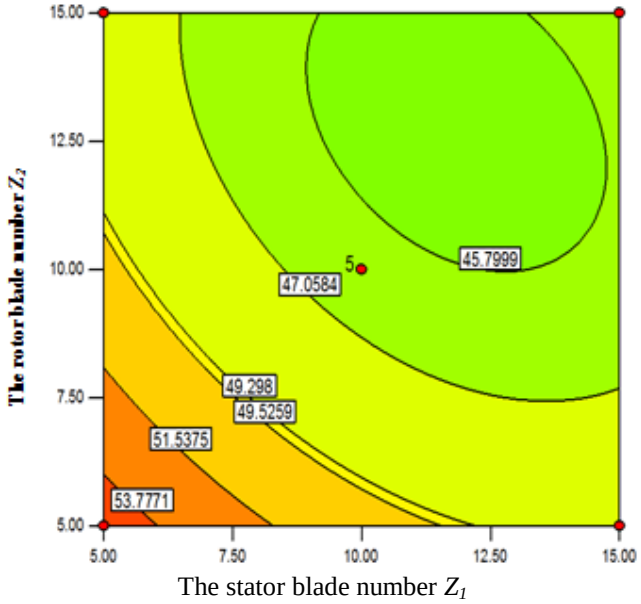


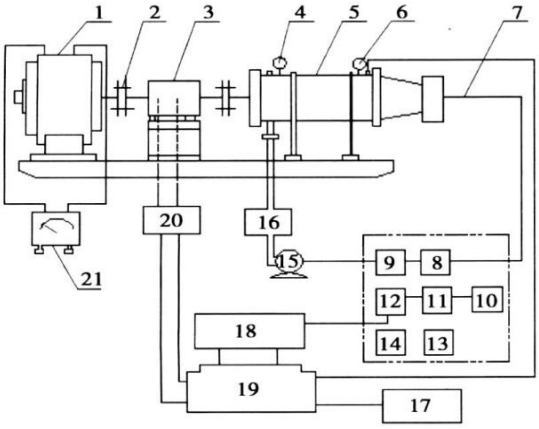
Fig.12 Impact of Z_1 and Z_2 on efficiency

VI. Experimental Verification and Results

An optimal design point is selected as the optimal turbine model, and the control parameters are β_1=46°, β_2=29.18°, Z_1=15, Z_2=5, m_1=2mm, m_2=5mm, θ_1=θ_2=60°, respectively. After the optimization design, parameters of rotor and stator are matched rationally to process molding turbine to conduct a test. The test is proceeded in a performance test bench with 10 levels of turbodrill in the lab of Southwest Petroleum University, and the test system diagram is shown as Fig.13. It shows the structure of the turbine bench, which mainly consists of pumping device, loading device, the body of bench, automatic control and data acquisition. In order to ensure a constant of the displacement of fluid, the closed-loop control system of displacement in multistage centrifugal pump is adopted. And the magnetic powder brake is chosen as a loading device controlled by the computer automatically. Then automatic control is conducted by the closed-loop device including the flow measurement, adjustment and execution part. Finally the data acquisition and processing are accomplished by the computer and data

processing software. To verify the reliability of the simulation model, the bench test of ten-stage turbines (Fig. 14) is performed with water instead of drilling fluid at a certain flow rate and different speeds for the characteristic of torque *M*, pressure drop ΔP and efficiency η, and the flow rate at the inlet is set to 27L/s, which can make the same normal speed to the simulation boundary condition. Then the testing instruments should be preheated by electricity more than 15 minutes, and the turbines are started at a low speed to make the bearings running in for 15 minutes.

A numerical flow field simulation of the design and the off-design turbine model is carried on, which is compared with experimental results. From Figs. 15-16, the initial value is the numerical simulation results of turbine with a symmetric structure. The predictive value denotes the numerical simulation results of turbine after optimizing design and matching. The experimental value is the result of the external characteristic test of the optimized turbine model.



1-Magnetic powder brake; 2-Coupling; 3-Torque speed sensor; 4-The pressure gauge; 5-Bench; 6- Pressure transmitter; 8- Electric control valve; 9-LWGB; 10-Manual station; 11-Servo amplifier;12- Flow totalizer; 13-Electric indicating controller; 14-Impedance converter; 15-Multistage centrifugal pump; 16-Water tank; 17-Printer; 18- Data sampling board; 19-Computer; 20-Torquemeter; 21- Stabilized current supply(Tunableness)

Fig.13. Diagram of turbine bench

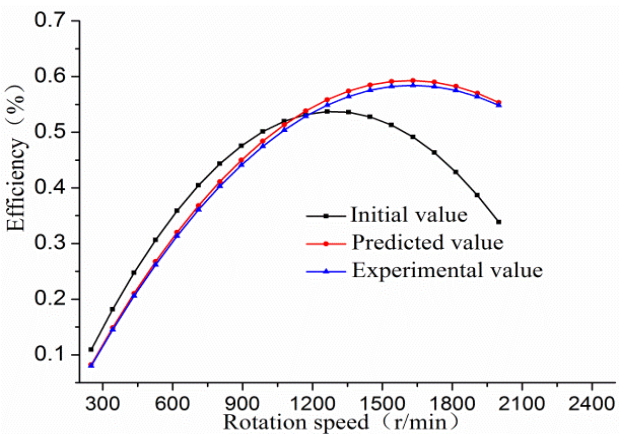


Fig.14 Comparisons of Efficiency

In the Figs. 14-15, the maximum initial efficiency value is about 55.309%, and the corresponding torque value is 9.068N·m when the rotation speed is 1250r/min. The maximum predicted efficiency can be up to 64.824% when the rotation speed is 1750 r/min, and its corresponding predictive torque value is 12.89 N·m. Hence, the efficiency value after optimizing match is increased by 10% than the initial value. From Fig.14, turbine efficiency is obviously improved when the rotation speed is bigger than 1200 r/min, and the high efficient area moves to the right. This is due to that the total number of turbine blades increasing after optimizing match, and the pressure loss is large in the low speed region, which leads to low efficiency. From the two diagrams, the relative error of experimental value is smaller compared with the predictive value, and the trends of performance curves are almost the same. It declares that the design method based on Box-Behnken and the orthogonal design experiments can be used in the matching analysis of asymmetric turbine's parameters.

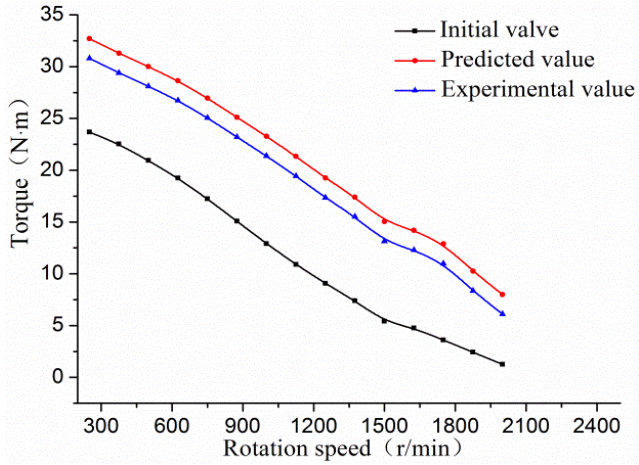


Fig.15 Comparisons of Torque

VII. Conclusion

(1) With the single-factor experimental design, sensitive analysis on the structural parameters was conducted. As a result, four significant factors of blades influencing efficiency were screened out, which included the stator's spiral angle β_1, the rotor's spiral angle β_2, the stator's blade number Z_1 and rotor's blade number Z_2. Also the four secondary factors can be obtained: the stator's blade thickness m_1, the rotor's blade thickness m_2, the stator's blade rotation angle θ_1 and the rotor's blade rotation angle θ_2.

(2) Based on the Box-Behnken design and response surface method, the mathematical model relating to the objective function and the blade variables was exactly established for the optimum combinations of parameters. The final eight parameter values are β_1=46°, β_2=29.18°, Z_1=15, Z_2=5, m_1=2mm, m_2=5mm, θ_1=θ_2=60°, respectively.

(3) The experimental study was conducted on the optimal design point of the asymmetric turbine. The results show that CFD simulations are in good accordance with the calculations based on response surface method, and the efficiency value after optimizing match is increased by 10% than the initial value. The relative error of experimental value is smaller compared with the predictive value, and the trends of performance curves are almost the same. It declares that the design method based on Box-Behnken can be used in the matching analysis of asymmetric turbine's parameters.

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