Study on Optimization of Impeller Structure Parameters of ESP for Offshore Oilfield Based on ANSYS

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Abstract. According to the initial design parameters of electric submersible pump and the profile equation of blade, the 3D model of impeller and internal flow passage of electric submersible pump is established in Pro/E. By using the APDL parametric modeling function of ANSYS, the optimal analysis model is established. The design variables, target variables and constraints were selected by referring to the relevant books and empirical formulas, and the structure was optimized by using the ANSYS optimization tool. The parameters before and after optimization of the impeller structure under the same viscosity and the optimization parameters of the different oil viscosity coefficients were compared to obtain the influence of each design variable on the performance of the ESP and the optimum parameters under different viscosity coefficients law, which provides a reference for determining the main design parameters of the electric impeller structure of ESP in offshore oilfield.

Keywords: Electric submersible pump · ANSYS · Optimal design · Impeller structural parameters · Oil viscosity

1 Introduction

With the adjustment of the energy structure, the development of marine resources has been paid more and more attention. In oil and other related industries, the fluid machinery and other equipment have played a pivotal role. As a kind of artificial mining method [1], ESP has the advantages of large flow, high power, strong adaptability, large working pressure, simple process, long service life, significant economic benefits and many other advantages. Because of these advantages of ESP, it has been widely used in the high water content, low gas ratio, low energy and other complex conditions of production wells [2].

Although the ESP has been widely used in offshore oil platform, but its production cost is much higher than the land, mining environment is relatively poor, and all kinds of work are more difficult than on land. For some complex conditions, the oil production still has a great difficulty, especially because of changes in temperature or moisture content caused by changes in oil viscosity. In the process of oil extraction, the viscosity coefficient of crude oil determines the flow performance, and the viscosity of the oil also affects the size of shear stress [3]. There is great practical significance to understand the

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characteristics of the viscosity of the crude oil and the flow law, and to optimize the impeller structure parameters of the ESP according to the size of the viscosity coefficient.

2 Establishment of 3D Model of Impeller and Internal Flow

According to the initial design parameters and the blade line equation, the complete single stage impeller solid model is established by Pro/E software, as shown in Fig. 1, and the impeller blade solid part is removed to generate the internal flow channel model. A single stage impeller 3D solid model as shown in Fig. 2.

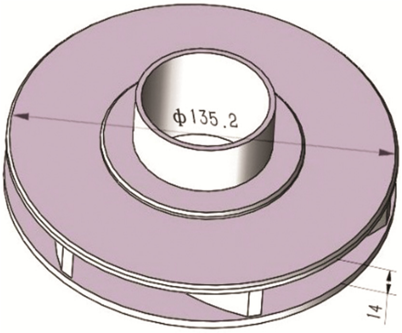

Fig. 1. 3D model of impeller

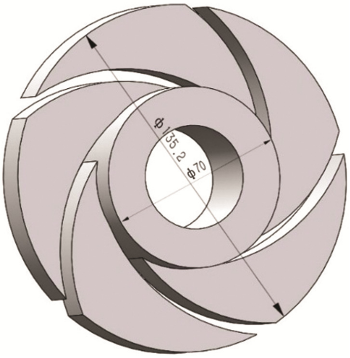

Fig. 2. 3D model of internal flow channel

3 Mathematical Model and Method of Optimization Design

In order to improve the performance of the submersible pump, it is necessary to make some constraints on the parameters with large influence on the impeller structure design, and use it as the constraint condition to optimize the structural parameters of the impeller. The inlet diameter D_1, outlet diameter D_2, inlet angle β_1, outlet angle β_2, outlet width b_1 and the number of blades z have different effects on the final performance of the submersible pump. Therefore, it is necessary to impose the necessary constraint on the optimal constraint equation. Based on the optimization method of finite element software ANSYS Workbench, the flow path model of impeller is modeled and then the simulation and optimization is carried out.

3.1 Optimized Mathematical Model

In general, the objective function and the constraint condition can be expressed as follows:

$$\begin{cases} minf(x) = f(x_1, x_2, \cdots\cdots, x_n) \\ x_{\min} \le x_i \le x_{\max} \quad i = 1, 2, \cdots\cdots, \mathrm{n} \\ \mathrm{g}_i(x) \le 0 \end{cases} \tag{1}$$

Where $x = (x_1, x_2, \cdots\cdots, x_n)$ is the design variable; $f(x)$ is the objective function; $g_i(x)$ is a state variable, a constraint function that contains equations and inequality constraints.

3.2 Determination of Constraint Condition and Objective Function

(1) Constraints of design variables

Appropriate choice of design parameters will help save time and reduce the amount of calculation. On the one hand, the value of the design variables cannot be too large, or do not meet the production requirements; on the other hand, if the value range is too small, it may deviate from the optimization point [4]. Therefore, it needs to consult the relevant design books and use the relevant empirical formula to give a reasonable range of design variables.

$$\begin{cases} 0.0631 \le D_1 \le 0.0721 \\ 0.1235 \le D_2 \le 0.1330 \\ 15^\circ \le \beta_2 \le 40^\circ \\ 20^\circ \le \beta_1 \le 35^\circ \\ 0.0144 \le b_2 \le 0.0231 \\ 3 \le z \le 8 \end{cases} \tag{2}$$

Where D_1 is the inlet diameter of the impeller, the outlet diameter of the D_2 impeller, β_2 is the impeller exit angle, β_1 is the impeller inlet angle, b_2 is the impeller exit width, and z is the number of blades.

(2) Constraints for state variables

The state variable constraint is a constraint that determines the structural material to meet certain performance requirements. Such as the allowable stress value of the material:

$$\sigma = \max(\sigma_i) \le [\sigma] \tag{3}$$

Where σ is the maximum equivalent stress on each impeller on the impeller; σ_i is the equivalent stress of the i node; $[\sigma]$ is the allowable stress of the material; i is the node number, $i = 1, 2, 3, \cdots\cdots, N$.

The ESP impeller commonly used materials for high nickel cast iron, containing more than Ni13%, has the mechanical process and good performance [5]. After the heat treatment, the yield strength is 345 MPa, and the safety factor is about 1.5:

$$[\sigma] = \frac{345}{1.5} = 230\ \text{MPa} \tag{4}$$

It can be concluded that the constraint of the state variables is:

$$0 < g_i(x) = \sigma \le 230 \tag{5}$$

Where $g_i(x)$ the stress function for the impeller.

(3) Objective function

The impact of the submersible pump head performance (efficiency and head) are the outlet pressure and outlet speed of the impeller, so choose model data as output target parameters to meet the equivalent stress conditions, so as to reach the maximum value. It can be concluded that the constraint condition of the objective function is:

$$min\, P_{static} = -f(x_1, x_2, x_3, x_4, x_5, x_6) \tag{6}$$

Where P_{static} on behalf of the export section of the static pressure size. $x_1, x_2, x_3, x_4, x_5, x_6$ represent the design variables D1, D2, β2, β1, b2 and z, respectively.

3.3 Performance Evaluation of ESP

Parameters of electrical submersible pump performance is its work efficiency and head size, formula (7) is the calculation of type ESP single stage head, formula (8) is the calculation of type ESP efficiency.

$$H = (P_2 - P_1) \Big/ \rho g + z_2 - z_1 + \frac{v_2^2 - v_1^2}{2g} \tag{7}$$

$$\eta = \frac{\rho g H Q}{1000N} \times 100\% \tag{8}$$

Where P_2 is the static pressure at the outlet, MPa; P_1 is the static pressure at the inlet, MPa; ρ is the oil density, kg/m^3; V_1 is the initial velocity of the entrance, m/s; V_2 is the speed at the exit, m/s; z_1 import height, m; z_2 export height, m; N is the shaft power, kw.

4 Optimization Calculations and Results Analysis

In this paper, the single-stage flow channel model is chosen as the research object, and the parameters of the single-stage impeller are optimized. Firstly, the optimum parameters of oil viscosity coefficient of 0.01 kg/m-s and density of 850 kg/m^3 were analyzed.

The initial sample data in the optimization process is randomly selected by software for 20 groups. After setting the initial sample data and running the analysis, the criterion of the optimization algorithm can be set in the ANSYS optimization module, that is the outlet pressure is the largest and the equivalent stress is the smallest. Different parameters can be set to the priority level, the maximum pressure at the outlet is set to the highest priority and the minimum equivalent stress is set to secondary priority. After updating the operation, three candidate parameter points are determined, as shown in Table 1.

Table 1. Optimized parameter candidate point.

SN	D_1/mm	D_2/mm	β_2/°	β_1/°	b_2/mm	z/个	P_{static}/Mpa	σ/Mpa
1	68.7	126.9	33.6	21.9	16.3	6.1	0.204	136.2
2	67.4	128.0	28.1	34.6	13.8	6.1	0.218	150.7
3	64.2	124.7	33.1	33.1	20.8	4.9	0.190	170.1

4.1 Optimized Performance Cloud Picture

The following figure shows the results of Fluent analysis. Figure 3 is the optimization of the overall pressure of the impeller cloud diagram; Fig. 4 for the optimization of the overall velocity of the impeller cloud diagram.

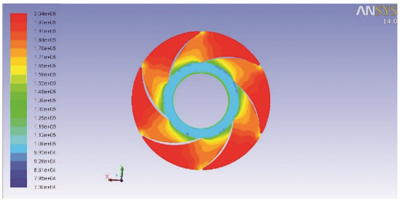

Fig. 3. Optimized pressure cloud diagram

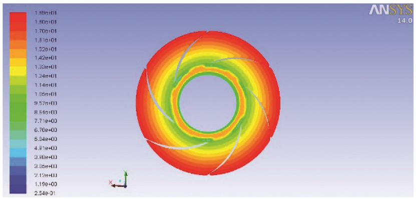

Fig. 4. Optimized velocity cloud diagram

As can be seen from Figs. 3 and 4, the optimized outlet pressure is about 2.04 × 105 Pa and the outlet velocity is 18.9 m/s. Therefore, it can be concluded by the formulas (7) and (8) that the efficiency after optimization reach to 52.7%

Figure 5 shows the deformation of the impeller blade after loading. Figure 6 is the equivalent stress distribution of the impeller blade.

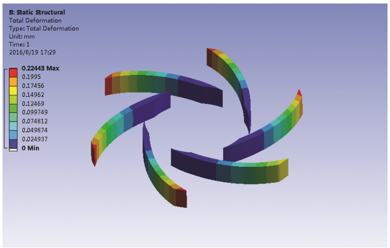

Fig. 5. Deformation cloud diagram

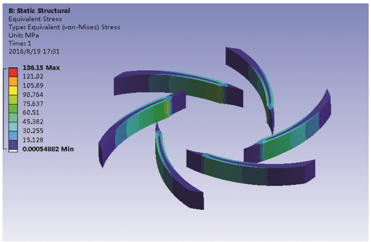

Fig. 6. Equivalent stress cloud diagram

It can be seen from the deformation cloud diagram that the maximum deformation of the impeller blades is 0.22 mm. According to the equivalent stress cloud, the maximum equivalent stress value of the impeller blades is 136.15 MPa, which is smaller than the allowable stress.

4.2 Comparison of Parameters Before and After Optimization

The oil viscosity coefficient of 0.1 and 1 kg/m-s were calculated and analyzed respectively.

(1) Comparison of data before and after optimization with a certain viscosity coefficient

Oil viscosity coefficient for the parameter optimization of ESP impeller structure before and after the 0.01 kg/m-s cases are shown in Table 2.

Table 2. Comparison of impeller structure parameters before and after optimization when the viscosity coefficient of oil is 0.01 kg/m-s.

Optimal variable	$D_{1/}$mm	$D_{2/}$mm	β_2/°	β_1/°	b_2/mm	z/piece	H/m	σ/MPa
Before optimization	70	135.2	35	25	14	5	10	139.79
After optimization	68.7	126.9	33.6	21.9	16.3	6.1	12.3	136.15

Through the comparison of the data in Table 2, it can be seen that the inlet diameter D_1, the outlet diameter D_2, the exit angle β_2 and the inlet angle β_1 of the impeller structure parameter are reduced to some extent, indicating that it is beneficial to improve the performance of the submersible pump when these parameters take a small value; while the export width b_2 is just the opposite, the optimized value is slightly larger than the previous one; the number of leaves is 6.1, which needs to be rounded to 6 in the modeling application.

(2) Comparison of optimization parameters for different oil viscosity coefficients

The data of the optimized parameters of the electric impeller of the ESP under different oil viscosity coefficients (0.01, 0.1, 1 kg/m-s) are shown in Table 3.

Table 3. Contrast of structural parameters of impeller under different oil viscosity coefficient.

Viscosity coefficient	D_1/mm	D_2/mm	β_2/°	β_1/°	b_2/mm	z/piece
0.01	68.7	126.9	33.6	21.9	16.3	6.1
0.1	67.4	126.1	34.1	21.4	17.3	5.6
1	66.5	125.1	35.0	20.8	18.8	5.9

By comparing the data in Table 3, it can be seen that the calculated impeller optimization parameters are different under different oil viscosity coefficients. With the viscosity coefficient of the oil increases, the values of the impeller inlet diameter D_1, the outlet diameter D_2, and the inlet angle β_1 are slightly reduced, which shows that the three parameters of a smaller value can help improve the performance of ESP. While the export angle β_2 and the outlet width b_2 is just the opposite, with the increase of oil viscosity coefficient, the number of these parameters will be slightly larger. For the number of impeller blades, the optimization value of the three kinds of oil viscosity has little difference, taking the number of 6 after the round.

5 Conclusion

In this paper, the optimal mathematical model is established by choosing the design variables, target variables and constraints using the relevant empirical formula, and the optimization analysis of the structure is carried out by ANSYS optimization tool. We can draw the following conclusions:

(1) The diameter of the inlet diameter of the submersible pump and the decrease of the outlet diameter will reduce the viscosity of the oil to a certain extent, which will help to reduce the energy loss and improve the efficiency of the ESP. The increase in export angle and entrance angle leads to a slight reduction in efficiency and pumping head. The number of leaves is too small, which makes the relative length of the runner becomes smaller. On the contrary, it will cause the flow channel is too narrow, increasing friction and causing energy loss.

(2) Under the condition of large oil viscosity, the lower value of the inlet diameter, outlet diameter and inlet angle will improve the performance of the submersible pump. The export angle and the width of the outlet is just the opposite, the larger value of these two parameters will improve the performance of the submersible pump; for the number of leaves of the impeller, the three oil viscosity optimization values are basically the same.

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