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Hydraulic optimization of impeller blade in reactor coolant pump base on Kriging model

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Abstract: To improve efficiency and head of the reactor coolant pump (RCP), an optimization approach is proposed based on Kriging model and genetic algorithm. 16 design cases containing three main parameters of blade, which are inlet angle β_1 , wrap angle φ , outlet blade angle β_2 , are designed by using the design of experiment(DOE) with Lation Hypercube. The efficiency and head are calculated by steady numerical simulation. The max efficiency and head under the design point $1.0Q_d$ are selected as the objective functions. Approximation models between the object and the parameters are built using Kriging model. The genetic algorithm is applied to optimize the approximation models to obtain the best combination of parameters. The results show that efficiency η has up to 51.54% at design flow rate. Comparing with prototype, the efficiency was increased by 1.02 percentage point, therefore the optimized RCP will save about 0.5×10^6 kW h energy a year. The optimization method can provide an effective reference to the improvement of pump's performance.

Key words: Optimization, Blade, design of experiment, RCP, Kriging model, Approximation model

1. Introduction

With the development of industry, the non-renewable energy (coal, oil, etc.) is being massive consumed, so energy is becoming increasingly tense. As a clean and highly efficient energy source, nuclear energy has received increasing attention.

A nuclear main pump is a pump in a nuclear island primary circuit that is used to drive a coolant to circulate in an RCP (Reactor Coolant Pump) system. The main pump is located in the heart of the nuclear island. RCP is used to transfer heat into the evaporator to convert heat energy and is the key to the operation of nuclear power to control the water circulation. Each steam generator has a main pump. RCP is the heart of the nuclear power plant, and it is the nuclear code class I equipment for controlling the coolant cycle in the nuclear island. In addition to considering safe operating factors, operating efficiency is an important factor to consider in designing RCP. The RCP is the main energy-consuming equipment of the nuclear power plant. The current main shaft power of the main pump shaft is in the range of 4,000-8,300kW. For a nuclear power generator unit with a single-machine power of 1400MW, the rated power

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of the nuclear main pump is about 7.7MW. A one percent increase in efficiency will save electricity by nearly 670,000 kW \cdot h a year. The impeller is one of the main components of RCP, and it is necessary to optimize the design of impeller.

In order to improve pump operating efficiency, researchers and experts have conducted extensive research on the optimal design method of impeller. Miyauchi [1] used an inverse design method to optimize the mixing pump blade load. Yu Zhiyi [2] used an iterative method of positive and negative problems to optimize the design of the gas-liquid mixing pump impeller, and the optimized maximum efficiency was 44%. Lai Xitao [3] used Kriging model and genetic algorithm to optimize the impeller structure of the centrifugal pump. The optimized impeller quality was reduced by 5.39%, and the material utilization rate was improved. Blade trailing angle and thickness of impeller and shroud diameter of high head deep-well pump were optimized using orthogonal experiment [4]. Wang Xiaofeng [5] used the Kriging model and the genetic algorithm to optimize the aerodynamic performance of the NACA0012 airfoil and improved the lift and drag performance. the orthogonal experiment optimization is widely used in pump design. Basing on orthogonal experiment optimization, the optimizing design was put forward for sewage pump type double-blade sewage pump design [6]. The main factors affecting pump performance were observed, and the pump performance characteristic was simulated and analyzed using solid-liquid flow. The effects of main parameter factor were investigated and acquired on the vortex pump by computational fluid dynamic, and an optimization scheme for design was obtained by extreme comprehensive analysis method, and the orthogonal test was verified by experiments [7]. Based on the theory of unequal head design [8] the control variable method is used to optimize the design of the impeller using orthogonal experiment, and the best design was put forward. Xing [9] used the orthogonal experiment to optimize axial pump, and effects of impeller, guide vane and inlet structure on pump performance were analyzed. The optimization of impeller and guide vane of low-speed multistage submersible pump was done [10], and the feasibility of orthogonal design combined with numerical calculation in pump optimization is verified. The main factors and secondary factors influencing performance of the space guide vanes in deep-well centrifugal pump were analyzed by CFX [11]. The influence of the inlet and blade angle of space guide vane on pump head and efficiency were analyzed [12].

In addition, the research of optimization design methods [15] mainly includes experimental optimization design and modern optimization design.

The test optimization design mainly includes orthogonal test design, center composite design, uniform design, and Latin square design. The modern optimization design mainly uses the approximate model to establish the functional relationships between the optimization objectives and the design variables, such as response surface model, neural network model and Kriging model, and then use the optimization algorithm (genetic algorithm, particle swarm optimization, simulated annealing, etc.) The function is optimized. In addition, this optimized design method has also been successfully applied to structural optimization and other fluid machinery fields.

For improving the operating efficiency of RCP design conditions, an optimization approach is proposed based on Kriging model and genetic algorithm to obtain the best combination of parameters. The optimization method can provide an effective reference to the improvement of pump's performance.

2. Structure and basic parameters of RCP

Typical pressure-water reactor (PWR) system is shown in figure 1. A PWR uses light water as the reactor coolant and moderator in the state of high temperature and high pressure not boiling in the reactor core using RCP(Reactor Coolant Pump) and sends the high-temperature and high-pressure water to steam generators to generate steam with heat exchangers for a turbine generator to generate electricity.



Figure 1. typical preceurezed-water reactor system [18]

The operating flow rate of RCP Q_d is 23790m³/h and the Head of RCP *H* is 95m. The number of impeller blade is 7, and the number of guide vane is 12. The impeller rotation speed is 1485r/min. the specific speed of RCP n_s is 450 r/min according to chinese standard, so RCP is a mixed flow pump as shown in figure 2. The blade of RCP impeller is shown in figure 3.



3. Numerical simulation of RCP

The fluid in the reactor core is not boiling and RCP inlet pressure is 15.16MPa and the operating temperature is 293°C. Since the Mach number of the main pump flow field in the actual operating environment is much less than 0.3, so it is an incompressible fluid flow in RCP. The equations of continuity and balance of momentum in RCP are given as

$$\frac{\partial V_i}{\partial x_i} = 0 \tag{1}$$

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$$\frac{\partial V_i}{\partial t} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 V_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} V_i V_j$$
(2)

where V_i is the velocity, x_i is the position, P is pressure, ρ is fluid density and v is the kinematic viscosity. The density of 742kg/m³, the thermal kinematic viscosity 9.42×10⁻⁸m²/s.

The details of computational grid for RCP was shown in figure 4. The un-structure mesh was generated by ANSYS-ICEM. Table 1 investigated the mesh independency with demonstrating that additional mesh did not change head by more than 0.25% comparing with design head shown in table 1, and the number of mesh was 5.81 million.



Figure 4. Mesh generation

Mesh	Inlet	Impeller	Guide vane	Volute	Total	Head/m	Deviation/%					
1	0.11	0.92	1.44	0.33	2.8	102.60	5.77					
2	0.13	1.35	1.89	0.4	3.77	100.60	3.81					
3	0.26	1.91	2.87	0.77	5.81	95.24	0.25					

 Table 1. Grid independency (×10⁶)

The physical model used in the solver is the Reynolds-Averaged Navier-Stokes equations and The Shear Stress Transport (SST) closure equations in the two-equation model are used. The transmission behavior of the shear pressure transmission turbulence model is determined by the eddy viscosity equation containing the limit number. The proper transport behavior can be obtained by an equation to the table of the eddy-viscosity

$$v_t = \frac{a_1 k}{\max\left(a_1 \omega, SF_2\right)} \tag{3}$$

$$v_t = \mu_t / \rho \tag{4}$$

$$F_2 = \tanh(\arg_2^2) \tag{5}$$

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$$\arg_2 = \max\left(\frac{2\sqrt{k}}{\beta'\omega y}, \frac{500\nu}{y^2\omega}\right) \tag{6}$$

$$\mu_t = \rho \frac{k}{\omega} \tag{7}$$

where v_t is transport behavior, μ_t is turbulence viscosity, F_2 blending function, ρ density, k turbulent kinetic energy, ω turbulent frequency, y is the distance to nearest wall, v is kinematic viscosity, coefficient of α_1 and β' is 0.56 and 0.09.

A mass flow inlet boundary condition is used at the pump's inlet, a pressure outlet boundary. No slip wall and scalable wall functions were used, and wall toughness is 0.03mm. The max y-plus was 159 with numerical calculation. Frozen rotor interface and transient rotor/stator interface between rotating zone and static zone were used to steady and unsteady simulation respectively.

4. Optimization methods

4.1 Parameters and rang of variations

Schematic diagram of blade mean line was shown in figure 5. In this optimization 3 blade mean lines was designed. The Lation Hypercube is an efficient experimental design method with the advantages of effective space filling capacity and the ability to fit second-order or more nonlinear relationships, so three main parameters of blade, which are inlet angle β_1 , outlet blade angle β_2 , wrap angle φ , are designed by Lation Hypercube using the design of experiment(DOE). The variables and range of variations were shown in table 2. While *i* equates to 1, the span of blade is near to hub, and when *i* equates to 2, the span is in the middle of blade, and when *i* equates to 3, the span is near to shroud.



Figure 5. Schematic diagram of blade mean line

Table 2 . Variables and rang of variations $(i=1,2,3)$							
Variables	From (°)	To (°)					
inlet angle β _{i1}	15	45					

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outlet blade angle β_{i2}	10	35
wrap angle <i>q</i> _i	70	110

4.2 Lation hypercube design

The efficiency values of each test scheme under design conditions were calculated using numerical simulations. The Kriging approximation model was used to establish an approximate function for efficiency and input variables. Finally, a genetic algorithm was used to find the optimal value for the approximate function, and the optimal combined geometric parameters of the RCP impeller were obtained. 16 design cases and efficiency results were obtained in table 3.

Table 3. Samples of numerical results using Lation Hypercube and CFD										
Number	$\beta_{l1(\circ)}$	$\beta_{l2}(\circ)$	φ_l (°)	β _{21 (°)}	β ₂₂ (°)	$arphi_2\left(^\circ ight)$	$eta_{31(^\circ)}$	$eta_{32}(^\circ)$	$\varphi_3(^\circ)$	η (%)
1	33.12	32.06	32.13	24.96	20.93	21.74	102.23	92.50	85.16	71.41
2	36.08	25.54	23.26	17.73	29.86	27.22	81.31	90.45	104.36	78.14
3	23.92	13.14	35.31	26.12	33.69	17.22	97.38	93.78	97.06	60.55
4	31.60	18.70	32.55	19.20	36.18	22.64	94.44	81.84	91.71	72.83
5	25.80	24.09	33.62	24.12	28.62	25.54	89.54	87.97	82.64	69.78
6	26.80	19.29	25.07	21.41	30.84	15.91	88.22	98.22	92.33	74.04
7	29.87	17.60	29.71	23.21	38.86	29.40	87.08	75.58	89.59	76.16
8	24.79	27.79	40.46	17.40	27.87	20.45	82.79	97.17	81.80	63.01
9	44.47	21.83	30.21	22.99	35.56	23.61	86.41	87.69	91.01	65.17
10	34.86	22.11	35.90	29.55	26.86	20.71	91.28	95.24	88.24	70.34
11	28.24	25.24	26.60	20.94	23.78	24.22	71.99	85.74	79.58	67.16
12	30.88	23.77	28.03	27.80	30.09	19.36	94.49	84.70	87.20	75.13
13	33.65	19.95	18.35	22.29	25.99	18.04	92.97	91.43	95.62	73.48
14	19.58	26.94	26.73	20.45	31.65	25.01	90.58	89.68	100.07	61.91
15	30.38	22.76	31.54	14.98	25.35	27.58	99.75	106.98	85.89	78.57
16	28.42	20.58	28.60	26.84	32.65	22.29	85.21	82.49	94.13	73.06

4.3 approximation model and genetic algorithm

An impeller scheme needs a lot of time and computer resources to consume from the geometric modeling to the numerical calculation and prediction. The number of experimental design schemes is limited, and the optimal impeller geometry parameters cannot be obtained quickly. Therefore, in the impeller optimization process, an approximate model is used. You can save calculation costs and find the optimal value within the design parameters.

An m-dimensional design variable $S=(s_1 \ s_2 \ \cdots \ s_m)^T$, and a response value $Y=(y_1 \ y_2 \ \cdots \ y_m)^T$, then the response value was defined as

$$Y = \beta F(s) + z(s) \tag{8}$$

The covariance between any two $z(s_i)$ and $z(s_j)$ were defined as

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$$Cov[z(s_i), z(s_j)] = \sigma^2 r(s_i, s_j)$$
(9)

$$r(s_{i}, s_{j}) = \prod_{d=1}^{q} \exp(-\theta^{d} \left| s_{i}^{d} - s_{j}^{d} \right|^{pd})$$
(10)

Where F(s) is a global regression model, β is a regression coefficient, and z(s) is a correlation function. The genetic optimization algorithm realizes the mechanism of adjacent reproduction through the method of grouping after grouping, so that the probability of cross-breeding of solutions close to the optimization is increased, and the convergence process of the calculation is accelerated. The defined population is 200, the maximum number of iterations is 60, the mating probability is 0.9, and the mutation probability is 0.09.

5. Results and analysis

The comparisons of variable and efficiency was shown in table 4. The efficiency η has up to 81.54% at design flow rate. Comparing with prototype, the efficiency was increased by 1.02 percentage point, therefore the optimized RCP will save about 0.5×10^6 kW·h energy a year. Head and efficiency comparison were shown in figure 6, and the Head of RCP in design condition is close to performance of prototype.

				•				•		
	$\beta_{^{I1}(\degree)}$	$\beta_{l2}(^{\circ})$	φ_l (°)	β_{21} (°)	$\beta_{22}(^{\circ})$	$\varphi_2(^\circ)$	$\beta_{31(^\circ)}$	$\beta_{32}(^{\circ})$	$\varphi_3(^\circ)$	η (%)
Prototype	40	34	78	33	25	95	20	11	100	80.52
Optimization	42	35	79	31	24	101	20	13	95.7	81.54
1.7 1.6 1.5 1.4 1.3 1.2 1.1 1.1 1.0 0.9 0.8 0.7 0.6 0.1 0.2 0.3	ototype timized	6 0.7 0.8 w rate Q/Q ₄	0.9 1.0 1		1.1 1.0 0.9 0.8 0.7 0.6 0.5 0.5 0.4 0.3 0.1 0.0 0.1 0.0	2 0.3 0.4	0.5 0.6 Flow ra		prototype optimized	

Table 4. Comparisons of variable and efficiency



The difference of blade shape was shown in figure 7. What major change was that the pressure side of blade is reduce and pressure surface in red color sinks down comparing with prototype in blue color.



Figure 7. Difference of blade shape (red: optimization, blue: prototype)

Flow information, streamline, turbulence kinetic energy and static pressure, of RCP with optimization was shown in figure 8. It is clearly found that the distribution of streamline, turbulence kinetic energy and static pressure was uniform, and the high turbulence kinetic energy was at root of the blade near hub and shroud. The optimized blade reduced energy loss, and the structure of blade is more adaptable to flow pattern in impeller channel.



Figure 8. Flow information of RCP with optimization (a: streamline, b: turbulence kinetic energy, c: static pressure)

6. Conclusions and discussions

An optimization approach is proposed based on Kriging model and genetic algorithm to obtain the best combination of parameters for improving the operating efficiency of RCP design conditions. The efficiency η has up to 81.54% at design flow rate. Comparing with prototype, the efficiency was increased by 1.02 percentage point, therefore the optimized RCP will save about 0.5×10^6 kW·h energy a

year. The optimization method this article presented can provide an effective reference to the improvement performance of RCP.

The blade of RCP is bent and twisted which has very complex three-dimensional structure. In the future study, the more parameters or variables should be taken into consideration, and an intelligent optimization should carry out.

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