

Orthogonal Optimization Design of Inlet Guide Vanes for Centrifugal Pumps (Postprint)

Authors: Hou Hucan, Zhang Yongxue, Li Zhenlin, Zhou Xin, Wang Zizhe

Date: 2017-11-07T00:00:00+00:00

Abstract

To investigate the influence of various design parameters of the inlet guide vane on the hydraulic performance of a centrifugal pump, the hydraulic design of its inlet guide vane was completed for an IS series centrifugal pump using a self-developed program based on two-dimensional theory. Applying an orthogonal array, the hub radius of the guide vane, the aspect ratio, the distribution law of setting angle n , and the velocity circulation at the outlet edge $C_{\#30}$; were selected as design parameters to conduct a 4-factor 3-level orthogonal design, yielding nine groups of guide vanes. Full-flow-path numerical calculations were performed on the centrifugal pump equipped with guide vanes, using head and hydraulic efficiency as evaluation indices, and range analysis was employed to identify the primary and secondary factors affecting its hydraulic performance, thereby obtaining the optimal scheme. The guide vane under the optimal scheme was manufactured and tested. The results indicate that the numerical simulation and experimental results are in good agreement. After comprehensive optimization, compared with the centrifugal pump without guide vanes, the pump equipped with guide vanes shows little change in head, a 1.43% improvement in hydraulic efficiency, a reduction in shaft power of 0.83 kW, and total energy consumption is reduced by approximately 2.06%, simultaneously verifying the feasibility and reliability of the orthogonal optimization method.

Full Text

Preamble

Optimization Design of Inlet Guide Vane in a Centrifugal Pump Based on Orthogonal Method

HOU Hu-Can, ZHANG Yong-Xue*, LI Zhen-Lin, ZHOU Xin, WANG Zi-Zhe
(College of Mechanical and Transportation Engineering, China University of

Petroleum-Beijing, Beijing 102249, China)
(Tel: 010-89733146/18611131756, Email: zhyx@cup.edu.cn)

Abstract: In order to study the influence of inlet guide vane (IGV) parameters on hydraulic performance of centrifugal pump, the hydraulic design of IGV was completed for one IS type centrifugal pump using in-house code based on two-dimensional flow theory. The L9(34) orthogonal table was implemented to design nine types of IGVs, which contains four factors with three levels: hub radius r , length-width ratio R/b , setting angle distribution n , and velocity circulation Cur at outlet edge. The whole flow field of centrifugal pump with IGV was numerically simulated at three operating points, and regarding its head and hydraulic efficiency as the evaluation targets and aided by variance analysis, the primary and secondary factors of the researched parameters were acquired and an optimal combination scheme was obtained. Then the hydraulic performance experiments for the optimal IGV were carried out and the results show that the numerical results agree well with experimental data. Comparing with that without IGV, the head of centrifugal pump with IGV changes not much while the hydraulic efficiency increases obviously by 1.43% and the shaft power decreases by 0.83 kW, saving the total energy consumption about 2.06%, which meanwhile verifies the feasibility and reliability of the orthogonal optimization method.

Key words: IGV; Centrifugal Pump; Orthogonal Optimization; Hydraulic Design; Numerical Simulation

0 Introduction

Centrifugal pumps are widely used in various technical fields with enormous total energy consumption, making energy-saving research highly significant [1]. Due to improper selection, unreasonable hydraulic design, and actual operating conditions that severely deviate from design requirements, most centrifugal pumps operate under off-design conditions with low efficiency, causing substantial energy waste. Practice has proven that pre-swirl regulation using inlet guide vanes can effectively improve the flow condition at the impeller inlet, thereby enhancing the hydraulic performance of centrifugal pumps under off-design conditions. Gui Shaobo [2] conducted full-flow-path three-dimensional turbulent numerical simulations of a centrifugal pump with inlet guide vane at different pre-swirl angles, obtaining external characteristics that agreed well with experimental data. Wang Haimin [3] performed experimental studies on inlet guide vanes with different airfoils, demonstrating that appropriate positive pre-swirl regulation can achieve energy-saving purposes.

Orthogonal experimental design is a method for studying multiple factors and levels, which selects test points based on orthogonality and features “uniform dispersion and neat comparability,” making the test method efficient and rapid. Although orthogonal test methods have been applied in pump design, no pub-

lished results have been seen for inlet guide vane design applications. Rong Guoping [4] pointed out that orthogonal experiments can fully analyze the influence 规律 of various factors on pump performance and obtain optimal results through the most economical approach. Zhang Jinya [5] optimized the impeller of a multiphase pump based on orthogonal design methods using numerical simulation, significantly improving the hydraulic performance of the multiphase pump. Shi Weidong [6] conducted orthogonal test optimization design for high-head deep-well centrifugal pumps and used range analysis to identify the primary and secondary factors affecting deep-well pump performance, proposing an optimal design scheme.

This study takes the IS150-125-250 model pump from the type spectrum as the test object. Based on two-dimensional flow theory, an in-house program was developed to complete the hydraulic design of a twisted spatial inlet guide vane. Guided by orthogonality, nine sets of inlet guide vane blades were designed and full-flow-path numerical simulations of the centrifugal pump with guide vane were conducted to explore the influence of different design parameters on the overall hydraulic performance of the pump and propose an optimal design scheme. Subsequently, the optimal inlet guide vane device was manufactured and hydraulic performance tests were conducted to verify the feasibility of the design method and the reliability of the results.

Funding: This research was supported by the China Petroleum Science and Technology Innovation Fund Research Project (2012D-5006-0611) and the China University of Petroleum-Beijing Young Teachers Special Training Fund Project (NO. KYJJ 2012-04-11).

1 Hydraulic Design of Inlet Guide Vane Based on Two-Dimensional Theory

The flow chart of the two-dimensional hydraulic design method with potential axial flow is shown in Figure 1 [Figure 1: see original paper]. First, the initial axial flow channel contour of the guide vane is determined; then the quasi-orthogonal line method is used to draw the axial flow net and perform iterative calculation of axial velocity [7]; next, the point-by-point integration method is employed for blade camber line shaping and double-sided thickening along the circumferential direction; finally, multiple Bezier curve rounding treatments are applied to the inlet and outlet edges of the guide vane, and its three-dimensional model is constructed in Gambit software [8] as shown in Figure 2 [Figure 2: see original paper]. In the design, the outlet edge of the guide vane adopts equal circulation design, while the inlet edge satisfies the non-impact condition at the impeller inlet after pre-swirl regulation under design flow rate to reduce impact losses.

The basic design parameters of the guide vane are: rim diameter 150 mm, design flow rate $Q_d = 200 \text{ m}^3/\text{h}$, number of blades 6, inlet setting angle 90.0° , and

axial distance 200 mm. The main geometric structural design parameters of the inlet guide vane include: hub radius r (r_1), length-width ratio R_{lb} ($l/(r_2-r_1)$), the fourth-order distribution law n of blade setting angle along the axial streamline, and the blade vortex Cur at the outlet edge. Whether the selection of these structural design parameters is reasonable directly affects the hydraulic performance, and appropriate parameter selection can improve the off-design hydraulic performance of the centrifugal pump while sacrificing only a small amount of head. Three levels were selected for each design factor as shown in Table 1, and the orthogonal test scheme determined using the $L_9(3^4)$ orthogonal table is shown in Table 2.

2 Numerical Simulation and Calculation Method

Based on the determined orthogonal scheme, numerical calculations were performed for the centrifugal pump with inlet guide vane for each scheme. Ansys Meshing was used for grid division of the centrifugal pump as shown in Figure 3 [Figure 3: see original paper]. Fluent software was used for full-flow-path flow field calculation, employing the RNG k -turbulence model and standard wall function. The MRF model was adopted for coupling of rotating and stationary components, and the SIMPLEC algorithm was used for pressure-velocity coupling solution. The PRESTO! scheme was used for pressure term discretization, second-order upwind scheme for convection term discretization, and second-order central difference scheme for other terms. Velocity inlet boundary condition was applied at the inlet, free outflow at the outlet, no-slip wall condition at solid walls, and Interface surfaces at rotor-stator interfaces for internal data transfer.

The head, shaft power, and efficiency of the centrifugal pump are calculated as follows:

$$H = \frac{p_2 - p_1}{\rho g} + \frac{v_2^2 - v_1^2}{2g} + \Delta z$$

$$P = \frac{M \cdot n}{9550}$$

$$\eta = \frac{\rho g Q H}{P}$$

where H is head, P is shaft power, η is efficiency, Δz is the elevation difference between pump inlet and outlet; p_1 , p_2 , v_1 , v_2 are the static pressure and velocity values at the inlet and outlet of the centrifugal pump (including inlet guide vane), M is torque, n is rotational speed, and ρ is fluid density.

3 Grid Independence Verification

To reduce computational load while ensuring calculation accuracy, grid independence verification must be performed as shown in Table 3 . The three characteristic quantities selected during the independence verification are head H , hydraulic efficiency η , and average blade vortex C_{ur} at the impeller inlet section under rated operating conditions. Through comprehensive analysis, Grid 4 was selected as the grid number for subsequent simulation calculations.

4 Analysis of Orthogonal Design Results

All full-flow-path numerical calculations were conducted at 0° pre-swirl angle, and the head and hydraulic efficiency of the centrifugal pump for the nine design schemes calculated under Q_d operating condition are shown in Table 4 .

Table 4 shows that the highest head is for Design Scheme 1 with $H = 16.27$ m, while the highest hydraulic efficiency is for Design Scheme 6 with $\eta = 85.91\%$. To analyze the influence of each design parameter on centrifugal pump performance and identify the main factors and optimal scheme, range analysis was performed on the simulation results as shown in Table 5 . In the table, K_i is the sum of simulation results at level i , M_i is the average value of results at level i , and R is the range. For intuitive visualization, line charts with factor level variation as the horizontal axis and index average value as the vertical axis are shown in Figure 4 [Figure 4: see original paper].

The range analysis in Table 5 shows that the influence patterns of the main design parameters of the centrifugal pump inlet guide vane on the overall hydraulic performance are different. The primary and secondary order of influence on H is $DBCA$, while that on η is $BDCA$, indicating that in the design of centrifugal pump inlet guide vane, priority should be given to the guide vane profile and blade vortex at the outlet edge. For individual factors: Factor A has influence order $A_1 > A_2 > A_3$ on H and $A_1 > A_3 > A_2$ on η ; Factor B has $B_3 > B_2 > B_1$ on H and $B_2 > B_3 > B_1$ on η ; Factor C has $C_1 > C_2 > C_3$ on H and $C_1 > C_3 > C_2$ on η ; Factor D has $D_1 > D_2 > D_3$ on both H and η . Based on comprehensive analysis, the optimal combination that improves hydraulic efficiency while considering head is $A_1B_2C_1D_1$.

The pre-swirl regulation of centrifugal pump with inlet guide vane can effectively improve its off-design hydraulic performance. The author selected small flow condition $0.8Q_d$ and large flow condition $1.2Q_d$ for numerical calculation, and the obtained head and hydraulic efficiency results are shown in Table 6 , with corresponding range analysis shown in Table 7 .

The range analysis in Table 7 shows that under $0.8Q_d$ condition, the primary and secondary order of influence on H is $DBCA$, while that on η is $ABDC$. Combining the influence results of individual factors, the optimal combination for improving hydraulic efficiency while considering head is $A_3B_2C_1D_1$. Under

1.2Qd condition, the primary and secondary order of influence on both H and h is DBCA. Combining individual factor influence results, the optimal combination from the simulation data under 1.2Qd condition is A1B3C1D1. Through comprehensive analysis of the three orthogonal test results, the final optimal combination is A1B2C1D1, meaning the fourth-order distribution law of guide vane setting angle along the axial streamline is -1.5, hub radius is 15 mm, length-width ratio of guide vane is 0.8, and blade circulation at guide vane outlet edge is $0.1 \text{ m}^2/\text{s}$.

5 Analysis of Optimization Results

Based on the parameter combination from orthogonal optimization design, the hydraulic design was performed to obtain the guide vane geometric model, and numerical calculation was conducted to obtain the performance curves of the centrifugal pump under corresponding pre-swirl conditions. To verify the reliability of the orthogonal design results, a set of optimal guide vanes at 0° pre-swirl angle was manufactured through injection molding, and hydraulic performance experiments were conducted on the centrifugal pump with the optimal guide vane. The experimental system flowchart and corresponding guide vane pipe section are shown in Figure 5 [Figure 5: see original paper]. The performance curves obtained from hydraulic experiments and numerical calculations for centrifugal pumps without and with the optimized guide vane are shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper].

Figure 6 shows that as flow rate increases, the head-flow curve of the centrifugal pump with guide vane becomes steeper than that without guide vane. As flow rate increases, the hydraulic loss caused by the guide vane pre-swirl device itself becomes significant, resulting in faster head decline.

The efficiency-flow curve of the centrifugal pump with guide vane is overall higher than that without guide vane, indicating that the introduction of the inlet guide vane improves the internal flow field of the centrifugal pump and broadens its high-efficiency region. Fitting results show that the optimal operating condition Q_{op} for the centrifugal pump without guide vane corresponds to a flow rate of $161.56 \text{ m}^3/\text{h}$, efficiency of 59.78%, and head of 16.72 m. At the same flow rate, the centrifugal pump with guide vane shows a 1.43% efficiency improvement, 0.83 kW power reduction, and 6.90% energy savings, while head decreased by 4.84%, resulting in total energy consumption savings of 2.06%. Within the range of $0.9\sim 1.1Q_{op}$, the overall efficiency is improved with an average value of 1.07%, power savings average 0.92 kW, and average energy consumption savings of 7.5%, achieving the purpose of improving efficiency and saving energy for centrifugal pumps.

The numerical results in Figure 7 [Figure 7: see original paper] show that at Qd, the head and hydraulic efficiency are 16.19 m and 86.90% respectively. Compared with the calculation results of the nine orthogonal design schemes,

the head decrease is not significant while hydraulic efficiency improves by nearly one percentage point. At 0.8Qd condition, head and hydraulic efficiency are 17.02 m and 83.46% respectively; at 1.2Qd condition, they are 13.51 m and 80.74% respectively. Both are relatively ideal compared with the orthogonal design results, verifying the feasibility of the orthogonal design method and successfully achieving the optimization design of centrifugal pump inlet guide vane using orthogonal design.

It can also be observed that the head-flow curve of the centrifugal pump with guide vane is lower than that without guide vane, with an average head reduction of about 0.6 m. The efficiency-flow curve is significantly higher near the rated flow rate, indicating that the introduction of the inlet guide vane improves the internal flow field and broadens the high-efficiency region. Fitting data shows that hydraulic efficiency at the rated operating point increases by 1.35%, and within the flow range of 0.8~1.2Qd, hydraulic efficiency improves by an average of 1.32%, which agrees well with experimental results. This demonstrates the reliability of the numerical simulation method and verifies the correctness of the orthogonal hydraulic design method applied to centrifugal pump inlet guide vane, showing that this orthogonal design is successful and achieves the expected purpose.

6 Conclusions

- (1) The orthogonal experimental design method can be successfully applied to the optimization design of centrifugal pump inlet guide vane. With the aid of full-flow-path numerical calculation, the optimal combination scheme A1B2C1D1 was obtained. Range analysis detailed that the hub radius and outlet edge velocity circulation of the inlet guide vane have relatively large influence on the design results.
- (2) Numerical calculation results basically agree with hydraulic experimental results, demonstrating the reliability of the numerical calculation results and verifying the successful application of orthogonal hydraulic design method to centrifugal pump inlet guide vane.
- (3) Compared with the centrifugal pump without guide vane, the head change is not significant when the guide vane is installed, while the hydraulic efficiency at optimal condition improves obviously by 1.43% and total energy consumption saves 2.06%, achieving the purpose of improving efficiency and saving energy for centrifugal pumps.

References

- [1] Yuan Jianping, Zhang Gaicheng, Chen Xiang. Operation adjusting meth-

ods for energy consumption of centrifugal pump [J]. Drainage and Irrigation Machinery, 2006, 24(5): 44-47. (in Chinese)

[2] Gui Shaobo, Cao Shuliang, Tan Lei, et al. Numerical simulation and experiment of inlet guide vane pre-whirl regulation for centrifugal pump [J]. Transactions of the Chinese Society for Agricultural Machinery, 2009, 40(12): 101-106.

[3] Wang Haimin, Zhou Caimin, Huang Xiong, et al. Influence of different air-foil inlet guide vanes on positive pre-whirl of centrifugal pump performance [J]. Transactions of the Chinese Society for Agricultural Machinery, 2012, 43(11): 129-133.

[4] Rong Guoping. Orthogonal experimental design and application in pump research [J]. Drainage and Irrigation Machinery, 1995, 13(1): 27-30.

[5] Zhang Jinya, Zhu Hongwu, Li Yan, et al. Optimization design of multiphase pump impeller based on orthogonal design method [J]. Journal of China University of Petroleum: Edition of Natural Science, 2009, 33(6): 105-110.

[6] Shi Weidong, Zhou Ling, Lu Weigang, et al. Orthogonal test and optimization design of high-head deep-well centrifugal pump [J]. Journal of Jiangsu University: Natural Science Edition, 2011, 32(4): 400-404.

[7] Zhang Yongxue, Zhou Xin, Ji Zhongli, et al. Hydraulic design and performance analysis of low specific speed centrifugal pump [J]. Journal of Drainage and Irrigation Machinery Engineering, 2013, 31(4): 300-304.

[8] Zhou Xin, Zhang Yong-xue, Ji Zhong-li, et al. Hydraulic design of low specific speed centrifugal pump impeller by numerical method [J]. Journal of China University of Petroleum, 2011, 35(4): 113-118.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.