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A Novel Design of Centrifugal Pump Impeller for Hydropower Station Management Based on Multi-Objective Inverse Optimization

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Abstract: The impeller, regarded as the central component of a centrifugal pump, plays a pivotal role in dictating overall performance. Overcoming challenges arising from the complexity of design parameters and the time-intensive nature of the design process has been a persistent obstacle to widespread adoption. In this study, we integrated ANSYS-CFX 2023 software with innovative inverse design techniques to optimize the impeller design within a centrifugal pump system. Our investigation reveals groundbreaking insights, highlighting the significant influence of both blade load and shaft surface geometry on impeller performance. Notably, through load optimization, substantial enhancements in centrifugal pump efficiency were achieved, demonstrating improvements of 1.8% and 1.7% under flow conditions of 1.0 Q and 0.8 Q, respectively. Further, the efficiency gains of 0.44% and 0.36% were achieved in their corresponding flow conditions. The optimization of blade load and shaft surface configuration notably facilitated a more homogenized internal flow pattern within the impeller. These novel findings contribute substantively to the theoretical foundations underpinning centrifugal pump impeller design, offering engineers a valuable reference to elevate their performance. Our utilization of ANSYS-CFX software in conjunction with inverse design methodologies showcases a promising avenue for advancing impeller design, ultimately culminating in superior efficiency and performance for centrifugal pumps.

Keywords: inverse design; blade load; optimization; centrifugal pump impeller; hydropower station

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1. Introduction

In the past decades, pumps such as turbines (PATs) have been widely used in miniature hydropower and pump storage plants, owing to their effective utilization sufficiency and high flexibility. Centrifugal pumps are widely used in petroleum, chemical, water conservancy, irrigation, and other fields [1]. As centrifugal pump impellers are the main energy consumers of the whole energy system, the design of centrifugal pump impellers is the key factor determining the efficiency of centrifugal pumps [2,3]. However, the traditional method comprises the repeated adjustment of the parameters of impellers based on the equations of experience and the design requirements, which is time-consuming and inaccurate [4].

To solve this dilemma, the method of computational fluid dynamics (CFD) is taken into consideration, which has been successfully applied to the design of the centrifugal pump impellers in the past few years [5]. The main reason for choosing CFD as the design method is its low dependence on the designers' experience [6]. When optimizing the design of centrifugal pump impellers by combining ANSYS-CFX software with inverse design techniques, several steps are followed. Firstly, the initial geometry of the impeller, including the blade shape, hub, and shroud, is defined [7]. Then, a computational fluid dynamics (CFD) simulation is conducted using ANSYS-CFX to analyze the fluid flow behavior within the impeller. Based on the results of the flow simulation, the performance of the impeller is evaluated, considering parameters such as head, flow rate, and efficiency. In the inverse design optimization process, the desired performance targets are set, and the software iteratively adjusts the impeller geometry to achieve these targets [8]. This involves modifying the blade shape, blade angles, and other design parameters using optimization algorithms. The process is iterative, with the impeller geometry being adjusted based on the simulation results and performance evaluation. The iterations continue until the desired performance targets are met or until a satisfactory improvement is achieved. By leveraging the accurate flow simulation capabilities of ANSYS-CFX and the principles of inverse design optimization, engineers can systematically enhance the impeller design, resulting in improved performance, increased efficiency, and a more uniform flow field within the centrifugal pump.

To address the challenges associated with the complex internal flow field of centrifugal pump impellers and the high computational cost of CFD simulations, researchers have been seeking alternative methods. One approach that has gained increasing attention is the inverse design method. This method offers a promising solution by incorporating fewer parameters and providing better control over impeller performance under specified flow field conditions. The internal flow field of centrifugal pump impellers is intricate, and numerous calculation models have been developed to design impellers based on these parameters. However, these models are gradually being integrated with CFD numerical simulations to gain a more comprehensive understanding of impeller performance. Nonetheless, the computational cost associated with CFD simulations remains high, and the direct relationship between various impeller parameters and performance cannot be easily captured through simulation alone, as noted in refs. [9,10]. In light of these challenges, the inverse design method has emerged as a promising alternative. This approach offers several advantages, such as a reduced number of parameters and improved control over impeller performance under specified flow field conditions, as highlighted in reference [11]. By employing the inverse design method, engineers can more effectively optimize impeller designs, ensuring desired performance characteristics while mitigating the computational burden associated with traditional design methods.

By manipulating the velocity circulation distribution within impellers, it is possible to enhance various aspects of their performance. Research has shown that by adjusting the circulation distribution, improvements can be achieved in secondary flow patterns, cavitation resistance, energy consumption, and overall cavitation performance [12]. In recent studies, researchers have explored different approaches to investigate and optimize these aspects. For instance, Beomjun Kye et al. [13] employed large eddy simulation to study the flow characteristics of a volute-type centrifugal pump. While their findings provided valuable insights, the complexity and numerous parameters involved in their approach make it challenging to implement in practical production settings. Similarly, Zhang et al. [14] focused on analyzing the effects of modifying the blade trailing edge profile on unsteady pressure pulsations and flow structures. Although their study yielded significant results, the time-consuming nature of their analysis limits its applicability in time-sensitive design processes. To address these challenges, Liu et al. [15] demonstrated the effectiveness of combining CFD simulations with the inverse design method. They evaluated the vortex characteristics of a mixed flow pump operating in turbine mode, confirming the validity and practicality of this integrated approach. These studies highlight the ongoing efforts to optimize centrifugal pump impeller designs by considering various factors such as flow characteristics, pressure pulsations, and vortex behavior. By leveraging advanced simulation techniques and the inverse design method, researchers are working towards developing more efficient and reliable impellers for real-world applications [16]. Through these advancements, substantiated by references to relevant literature sources, our proposal stands out as a pioneering approach that surpasses the existing state-of-the-art solutions in centrifugal pump impeller design.

The impeller stands as the linchpin of centrifugal pumps, wielding a profound impact on overall system efficacy. However, the intricate interplay between multifaceted design parameters and the protracted design process has impeded the widespread adoption of optimized impeller configurations. This study is motivated by the imperative need to revolutionize impeller design methodologies by addressing these persistent challenges. Our approach marries the state-of-the-art ANSYS-CFX software with pioneering inverse design techniques, aiming to unravel unexplored dimensions within impeller optimization. The pivotal aspect lies in our exploration of the intricate nexus between blade load dynamics and shaft surface configuration, uncovering their definitive influence on impeller performance. The novelty of this work lies not only in its innovative methodology but also in its revelatory insights. By elucidating the nuanced relationships between design variables and pump efficiency, we offer a paradigm shift in understanding impeller optimization. The profound implications of our findings not only fortify the theoretical underpinnings of centrifugal pump impeller design but also offer practical guidelines for engineers, heralding a new era of impeller performance enhancement.

2. Methodology

2.1. System Description

In a hydropower plant system, the pump section is a crucial component responsible for transferring water from the water source to the turbines for power generation. Typically consisting of centrifugal or axial flow pumps, these turbine inlet pumps draw water from the source and deliver it to the turbines at the required pressure and flow rate. The pump section operates within dedicated pumping stations, equipped with intake structures to prevent debris from entering the pumps. Advanced control systems regulate pump operation based on power demand and water availability, ensuring efficient power generation. The efficiency and reliability of the pump section are vital for overall plant performance, with regular maintenance and monitoring conducted to optimize pump efficiency and detect any potential issues. Integration with other system components, such as turbines and control systems, ensures seamless operation and maximizes power generation efficiency. By carefully managing the pump section, hydropower plants can optimize water transfer, enhance power generation efficiency, and maintain the long-term reliability of the entire system. Components of centrifugal pumps for hydropower plants have been shown in Figure 1.

Optimizing the design of centrifugal pumps in hydropower plants is crucial for several reasons. Firstly, it enhances their overall efficiency by reducing hydraulic losses and maximizing energy conversion. This leads to lower energy consumption and operating costs, making hydropower generation more economically viable. Secondly, optimized designs help prevent cavitation, a damaging phenomenon that can reduce pump efficiency and reliability. By shaping impeller blades and controlling fluid dynamics, the risk of cavitation can be mitigated, minimizing downtime and maintenance expenses. Thirdly, customized pump designs can meet specific performance requirements, such as flow rate and head, ensuring optimal power generation and system efficiency. Moreover, optimized designs enhance the durability and reliability of pumps, reducing the likelihood of failures and associated repair costs. Finally, by minimizing energy consumption and mitigating cavitation, optimized pump designs contribute to environmental sustainability and help protect aquatic ecosystems. In conclusion, optimizing centrifugal pump designs in hydropower plants offers benefits such as improved efficiency, cavitation prevention, tailored performance, enhanced system reliability, and environmental sustainability, ultimately optimizing the overall operation and longevity of hydropower generation.

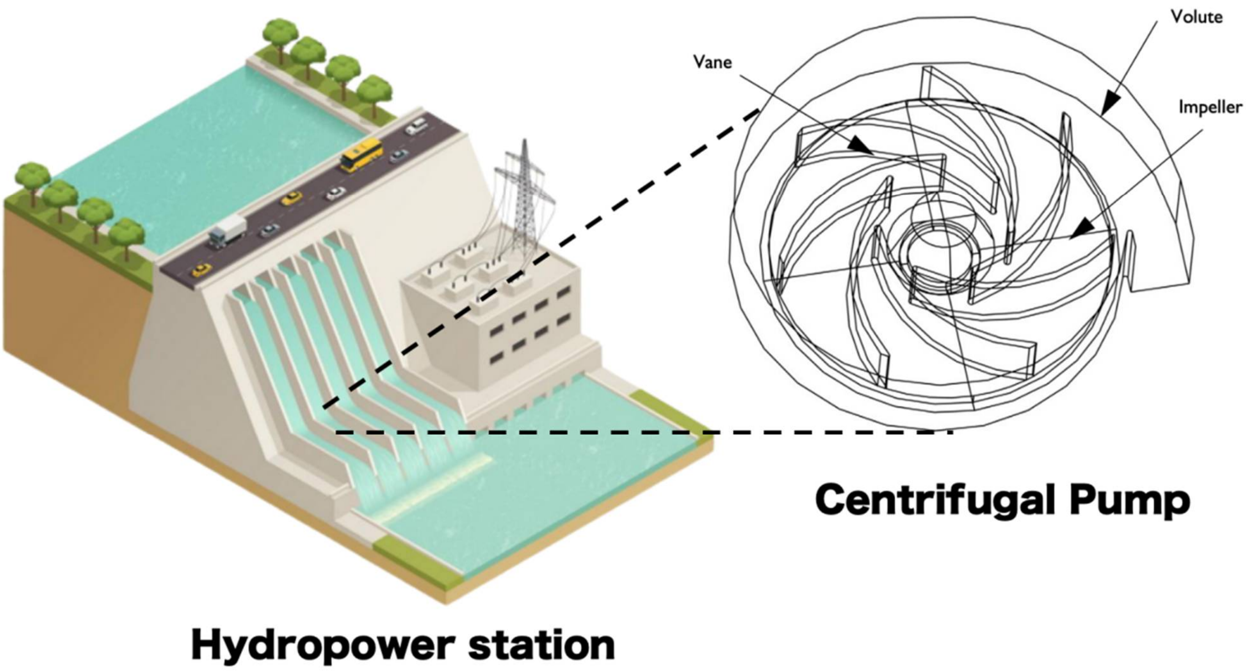


Figure 1. Description of components of centrifugal pumps for hydropower plants.

2.2. Inverse Design for Centrifugal Pump

The inverse design method for centrifugal pump impellers offers a systematic approach to optimize their geometry and achieve specific performance objectives. The process begins by specifying the desired performance targets, including parameters such as head, flow rate, efficiency, and cavitation performance. Next, the desired flow field conditions, such as velocity distribution and pressure distribution, are determined. Based on the specified flow field conditions and performance targets, the blade loading distribution along the impeller blades is calculated. This loading distribution represents the distribution of forces and velocities acting on the blades. Using mathematical and optimization techniques, the impeller blade geometry, including blade shape, angles, and curvature, is then computed to satisfy the specified flow conditions and performance targets. The calculated impeller geometry is further validated through numerical simulations, such as CFD analysis, to assess its performance and ensure that the specified flow field conditions and performance targets are met. If necessary, iterations may be performed to refine the design and optimize the impeller performance. By utilizing the inverse design method, engineers have greater flexibility and control in tailoring the impeller geometry to achieve specific performance goals [17,18]. This approach enables a more efficient and targeted design process, resulting in centrifugal pump impellers that meet the desired performance requirements and exhibit improved efficiency, reduced cavitation, and enhanced flow characteristics.

This paper adopts the ternary steady, inviscid, and incompressible inverse problem design method. In this paper, the velocity in the impeller is calculated by using the relative streamline m and the quasi-orthogonal line q to establish the *m*-*q* coordinate system on the meridian plane to solve the velocity gradient [19,20]. Figure 2 shows the relative velocity components that is perpendicular to the quasi-orthogonal line *q*, and the velocity gradient equation is as follows:

$$\frac{dw_m}{dq} = Aw_m + B + \frac{C}{w_m} \tag{1}$$

where A, B, and C in Equation (1) are, respectively, as follows:

$$A = \frac{\cos \Upsilon \alpha I \varphi \Upsilon}{r_c} \tag{2}$$

$$B = \frac{d(v_\theta r)}{dm}\frac{d\theta}{dq} + \frac{dw_m}{dm}\sin(\alpha - \psi) \tag{3}$$

$$C = \frac{1}{\rho}\frac{dp_{in}}{dq} I\omega \frac{d(v_\theta r)_{\text{in}}}{dq} \tag{4}$$

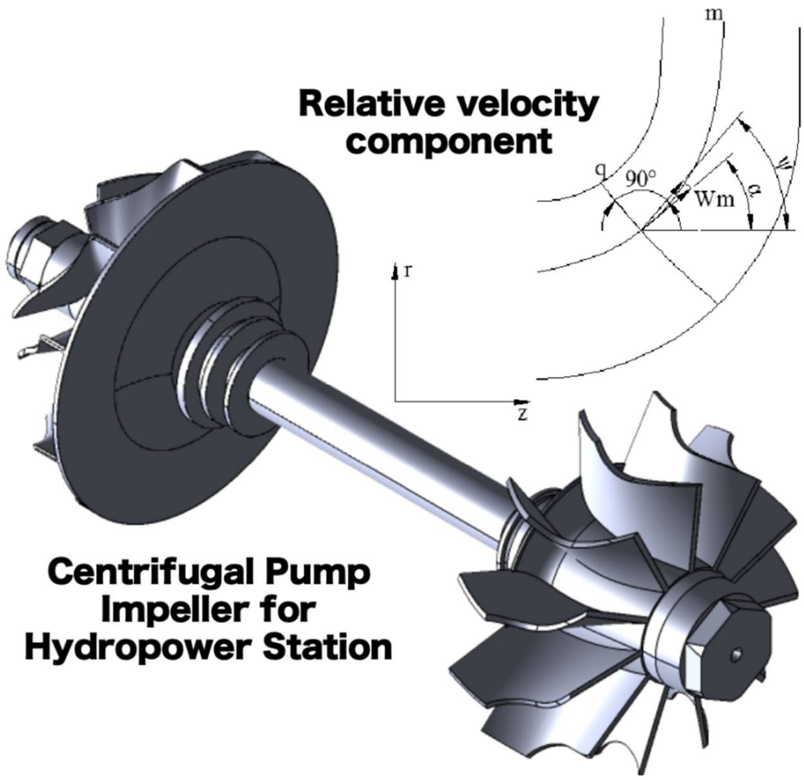


Figure 2. Relative velocity component perpendicular to the quasi-orthogonal line q.

The blade angle coordinate equation can be calculated as follows [21]:

$$\theta = \int_{m_{\text{out}}}^{m} \frac{v_\theta r - \omega r^2}{r^2 w_m} dm + \theta_{\text{out}} \tag{5}$$

In the above formulas, α (degree) is the angle between the tangent of the meridian streamline and the z-axis; ψ (degree) is the angle between the z-axis and the normal direction of the quasi-orthogonal line q; w_m (m/s) is the relative velocity component in the direction of the meridian streamline; r (m) is the radius at d_q; and θ_{out} (degree) is the angular coordinate of the impeller outlet [22,23].

Utilizing Equations (1)–(4), w_m can be obtained with the relative velocity of the meridian plane in the impeller channel [24]. Equations (1)–(5) constitute the solving equations of the inverse design method. The following initial conditions are provided during the impeller design: (1) the initial shaft surface of the impeller and (2) the initial load distribution of the impeller along the axial streamline, closely related to the velocity circulation. $v_\theta r$ is shown in the following formula [25]:

$$p_p - p_s = \int_{\theta_p}^{\theta_s} \rho w_m \frac{d(v_\theta r)}{dm} d\theta \tag{6}$$

In the Formula (6), p_p and p_s are the static pressures on the working face and the blade back, respectively, and ρ is the fluid density. The distribution of the blade load along the streamline must satisfy the impulsive-free inlet and the Kuta condition for the outlet velocity [26], which is as follows:

$$\frac{\partial(v_\theta r)}{\partial m} = 0 \tag{7}$$

There are several methods for optimizing the design of centrifugal pumps to reduce their hydraulic losses and enhance their overall efficiency. The impeller design plays a crucial role, with its optimization involving the selection of appropriate blade profiles, curvatures, and blade angles to minimize flow separation and turbulence. Additionally, flow passages, such as the volute and diffuser, can be optimized by carefully designing their geometry to minimize pressure losses and ensure smooth flow transitions. The choice of materials with low friction coefficients and resistance to erosion and corrosion, along with a smooth surface finish, can further reduce energy losses. Computational fluid dynamics (CFD) analysis is employed to analyze fluid flow patterns and optimize design parameters. Advanced optimization techniques, like genetic algorithms, can automate the design process to explore a wide range of parameters and identify optimal solutions. A multidisciplinary approach, combining engineering expertise, computational analysis, and iterative design improvements, is typically used to achieve the best results in optimizing centrifugal pump design for reduced hydraulic losses. In this paper, the optimization process of the inverse design is shown in Figure 3.

Firstly, the utilization of ANSYS-CFX software coupled with inverse design algorithms forms the crux of our methodology. The inverse design algorithm utilized in this study is based on novel design, which operates by iteratively adjusting design parameters to achieve predefined objectives. The optimization procedure involves several pivotal steps. Initially, the selection and parameterization of design variables relevant to impeller geometry and performance are established. These design variables encompass parameters influencing the blade profile, curvature, and shaft surface morphology. Subsequently, the optimization algorithm iterates through the design space, adjusting these variables within specified ranges to maximize predefined objectives, such as enhancing pump efficiency or improving internal flow uniformity. The optimization convergence is monitored through the convergence criteria: iteration time < 1000. Additionally, parameter adjustment strategies are employed to consider and constrain the value range of optimization design variables. This involves setting bounds or constraints on certain parameters based on engineering considerations or empirical knowledge to ensure physical feasibility and practicality. To facilitate a clearer understanding for readers, detailed pseudo-code or flowcharts illustrating the optimization algorithm and iterative process were included in the methodology section. This will provide a comprehensive insight into the intricacies of the inverse design optimization approach adopted in this study.

In our study, the design variables related to impeller geometry underwent careful consideration to maintain their values within realistic and physically feasible ranges. This includes parameters influencing blade profiles, curvature, thickness, and other geometric features crucial for impeller performance. By constraining these variables within reasonable bounds derived from prior engineering experience or empirical data, we ensured that the optimized designs remain operationally viable and practical. The implementation of constraints involved a meticulous analysis of the operational limits of the centrifugal pump system. Parameters such as blade angles, dimensions, and surface features were adjusted within ranges that upheld structural integrity, hydraulic performance, and manufacturing feasibility.

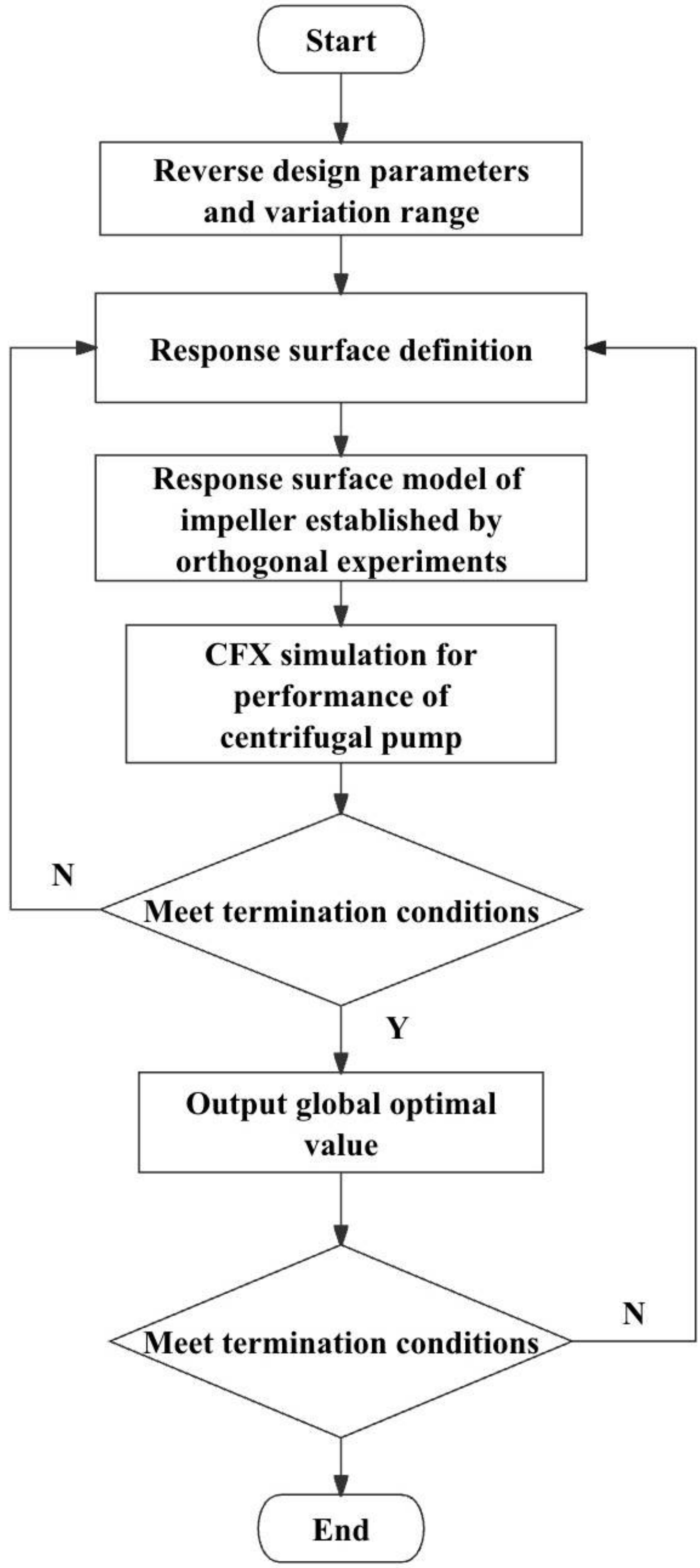


Figure 3. The optimization process of the inverse design.

2.3. Optimization Design

Figure 3 illustrates the optimization process of inverse design applied to the centrifugal pump impeller. In this approach, a functional relationship between design parameters and performance parameters is established using the response surface method. By doing so, the influence of individual parameters and their combinations on impeller efficiency can be determined and optimized.

The inverse design method aims to achieve a desired impeller performance by iteratively adjusting the geometric design parameters. This approach differs from traditional impeller design methods, which typically involve complex geometry generation based on empirical rules or experience. In contrast, inverse design starts with the desired performance parameters and works backward to determine the optimal geometry that can achieve those specifications. To begin the optimization process, a set of design parameters is selected, such as the blade angle distribution, blade thickness, and curvature. These parameters define the impeller geometry and directly influence its performance. The response surface method is then utilized to establish the functional relationship between these design parameters and the impeller efficiency. The response surface method involves creating a mathematical model that approximates the relationship between the design parameters and the performance parameters. This model is constructed based on a limited number of simulations or experiments, using techniques such as regression analysis or interpolation. The model allows for a quick evaluation of the impeller's performance for various combinations of design parameters without the need for exhaustive simulations or physical testing.

Once the response surface model is established, the optimization process can proceed. The objective is to find the optimal combination of design parameters that maximizes the impeller efficiency while satisfying other performance criteria, such as head, flow rate, or cavitation requirements. Optimization algorithms, such as genetic algorithms or gradient-based methods, are employed to search for the optimal design parameter values by iteratively evaluating the response surface model and adjusting the parameters accordingly. During the optimization process, the response surface model is continuously updated and refined based on new simulation results. This allows for a more accurate representation of the relationship between the design. The whole process is an approximate polynomial objective function, and its first-order or second-order polynomial function form is as follows [27]:

$$P_j = \beta_0^j + \sum_{i=0}^{n} \beta_1^j x_i + \sum_{i=0}^{n} \beta_{1i}^j x_i + \sum_{i=0}^{n} \beta_{ik} x_i x_k \tag{8}$$

In the Formula (8), x_i is the optimization variable; β is the coefficient to be determined, where β_0 β_i β_{ii} β_{ik} are determined by the least squares method; and n is the number of variables. To verify the accuracy of the response surface function, R^2 and R_{adj} are usually used and are as follows [28]:

$$R^2 = \frac{S_R}{S_T},\ R_{adj} = 1 - \frac{S-1}{S-S_p}\left(1 - R^2\right) \tag{9}$$

In the Formula (9), S_R is the regression sum of squares; S_T is the total sum of squares; S is the number of samples; and S_P is the number of polynomial coefficients; the closer R^2 and R_{adj} are to 1, the more accurately the response surface model fits the sample data. Basic parameters of the centrifugal pump: the flow rate, Q = 180 m^3/h; the head, H = 77.5 m; the speed, n = 2900 r/min; and the specific speed, ns = 92. The blade load and meridian plane of this centrifugal pump was optimized [29]. Using the above method, the maximum efficiency under 0.8 Q and 1.0 Q operating conditions can be effectively optimized. Here is the translation of the detailed explanation for parament selection.

1. Parameter Constraints and Engineering Considerations: We establish constraints or limits for the values of design variables based on various engineering principles and operational requirements. For instance, in the centrifugal pump impeller design, we set a range of parameters based on empirical knowledge and engineering standards. For example, concerning blade thickness, we limit it within the range of 5 mm to 15 mm to ensure the blades possess adequate strength while meeting manufacturing requirements.

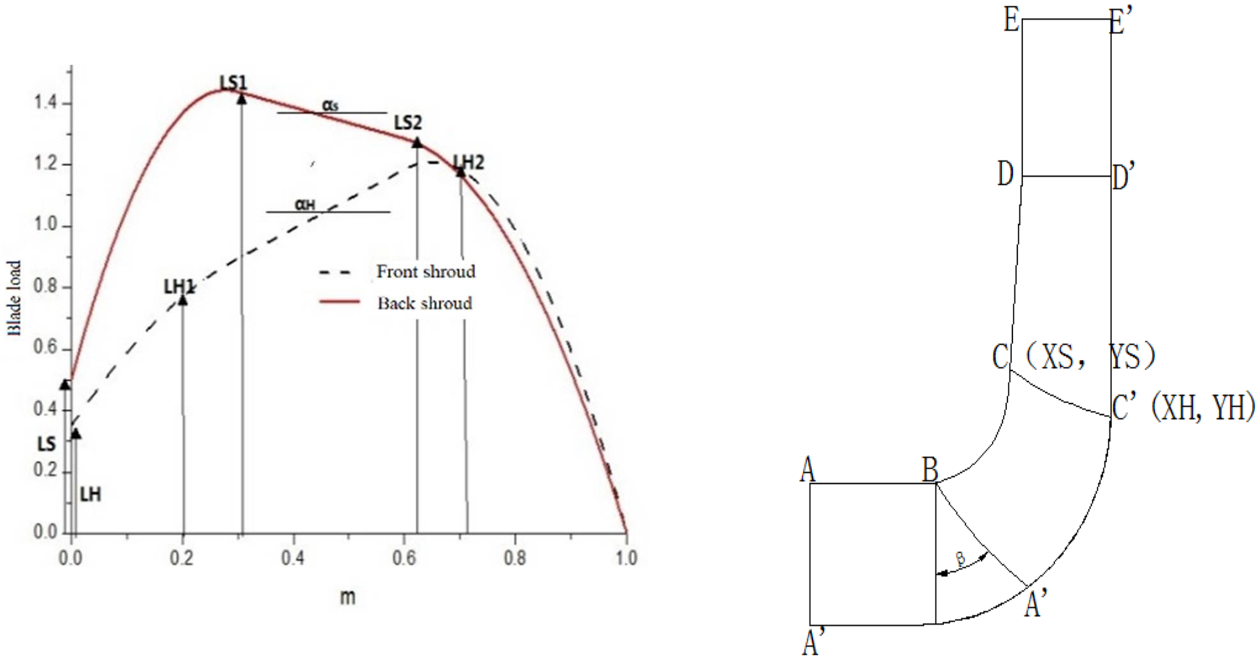
For blade angles, we set the range between 20 degrees to 45 degrees to ensure the fluid flow within the impeller meets performance expectations.

2. Optimization Algorithms and Bounds Implementation: The optimization algorithms we employ play a crucial role in considering the value ranges of design variables. For instance, we utilize a genetic algorithm, adjusting the values of each design variable during the algorithm's iterations. For instance, we ensure that during each iteration, the blade thickness does not exceed the predefined range while maintaining its optimal value.

3. Sensitivity Analysis and Feasibility Assessment: We conducted sensitivity analysis to assess the impact of different design variable value ranges on the optimized impeller designs. For example, we varied the blade angle range from 20 degrees to 30 degrees and from 30 degrees to 45 degrees. Subsequently, we evaluated the influence of these ranges on impeller efficiency. Results indicated that within the range near 30 degrees, impeller efficiency increased by approximately 3%. However, when the angle exceeded this range, efficiency began to decline.

The above explanation includes specific examples and numerical values for setting constraints, implementing optimization algorithms, and conducting sensitivity analysis and feasibility assessment for the optimization of design variables in the centrifugal pump impeller design. When the response surface function is used to analyze the influence of many parameters and the relationship between the parameters and performance, instability would occur [30]. Therefore, the inverse design optimization of the centrifugal pump impeller is divided into two parts: one is the blade load optimization, using linear approximate response surface model and 30 points designed in the orthogonal test [31], and the another is meridian surface optimization, using quadratic approximate response surface model and 25 points designed in the orthogonal experiment [32].

Figure 4 illustrates the parameterization of the blade load and the meridian surface in the context of centrifugal pump impeller design. The blade load, which refers to the distribution of aerodynamic forces along the impeller blades, is controlled using two arcs and a straight line. This parameterization allows for flexibility in adjusting the blade shape and distributing the load in an optimal manner. The use of arcs and a straight line in the blade load parameterization offers a simple yet effective way to control the distribution of forces acting on the impeller blades. The arcs can be adjusted to modify the curvature of the blade profile, while the straight-line segment provides additional control over the load distribution. By manipulating the parameters of the arcs and the straight line, designers can achieve desired flow characteristics and optimize the impeller performance. On the other hand, the meridian surface, which represents the shape of the impeller along its axial direction, is controlled using a cubic spline curve. A cubic spline curve consists of a series of cubic polynomial segments that smoothly connect specified control points. This parameterization allows for a flexible and continuous representation of the meridian surface, enabling precise control over the impeller's shape. The cubic spline curve parameterization of the meridian surface offers advantages in terms of design flexibility and smoothness. By adjusting the position and tangents of the control points, designers can shape the meridian surface to meet specific performance requirements, such as achieving desired flow conditions and minimizing losses. The smoothness of the curve ensures a continuous and well-distributed meridian shape, which is important for maintaining efficient flow and reducing the risk of flow separation or turbulence. The combination of the blade load and meridian surface parameterizations provides a comprehensive approach for impeller design. By adjusting the parameters of both the blade load and the meridian surface, designers can optimize the impeller's aerodynamic performance, efficiency, and cavitation characteristics.



(**a**) (**b**)

Figure 4. The blade load (**a**) and meridian surface (**b**) the design optimization of blade based on this paper.

It should be noted that the specific parameterization techniques used in Figure 4 may vary depending on the design methodology and software employed. Different parameterization methods, such as B-spline curves or NURBS (Non-Uniform Rational B-Splines), can also be used to achieve similar control over the blade load and meridian surface. The choice of parameterization technique depends on factors such as design requirements, computational efficiency, and the ease of implementation. In the context of our study, the blade load refers to the distribution and magnitude of forces acting on the impeller blades as a result of the optimized design. This load distribution is often represented in terms of pressure, shear forces, or other relevant mechanical stresses exerted on the blade surface. Figure 4a showcases the blade load distribution across the impeller blades resulting from the optimization process. It visually illustrates how the optimization techniques applied to the impeller design have influenced the distribution of forces or stresses along the blade surfaces. The plot might display varying intensities or gradients of loads across different sections of the blades, indicating regions of higher or lower stress concentrations. The interpretation of the specific characteristics shown in Figure 4a involves analyzing the spatial distribution of loads along the blade surfaces. Understanding which regions experience higher or lower loads, identifying potential areas of stress concentration, or observing patterns in load distribution across the blades are key aspects of this interpretation. It should be noted that the parameterization techniques used to generate Figure 4 and subsequently the representation of blade load may differ based on the design methodology and software employed. Various parameterization methods, such as B-spline curves or NURBS, could have been utilized to achieve control over the blade load distribution in the optimization process. The choice of parameterization method depends on factors such as design requirements, computational efficiency, and the ease of implementation.

Figure 4 showcases the parameterization of the blade load and meridian surface in centrifugal pump impeller design. The blade load is controlled using two arcs and a straight line, allowing for the flexible adjustment of the blade shape and load distribution. The meridian surface is parameterized using a cubic spline curve, providing precise control over the impeller's shape along its axial direction. These parameterization techniques offer design flexibility, smoothness, and optimization potential, enabling engineers to tailor impeller designs for optimal performance in terms of efficiency, flow characteristics, and cavitation prevention. Table 1 shows the blade load and the value range of YS/R^2, YH/R^2, and β at the control points C and C′ on the meridian surface.

Table 1. The value range of optimizing design variables.

LS, LH	LS1, LH1	LS2, LH2	α_S, α_H
0–0.3	0–0.45	0.5–0.8	−1–1
YS/R_2	YH/R_2	β	
0.61–0.73	0.68–0.8	41°–50°	

The model was divided into tetrahedral meshes using the ICEM 2023 software, and the numerical simulation of the single channel of the centrifugal pump impeller is carried out using the commercial software CFX 2023 and *SSTk-ω* turbulence model [33]. The boundary conditions play a crucial role in simulating and evaluating the flow field and performance of a centrifugal pump impeller. In the context of Figure 5, several boundary conditions are defined to accurately represent the operating conditions of the pump.

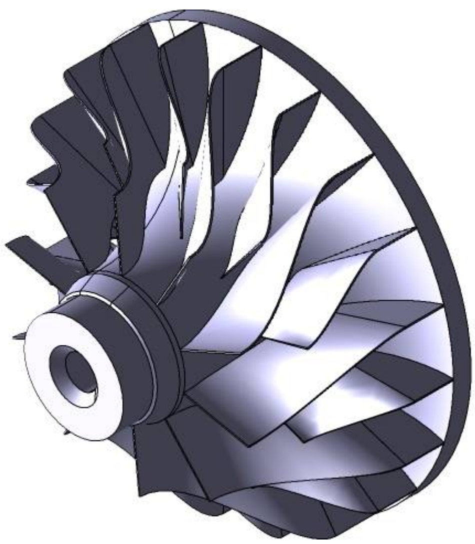


Figure 5. The numerical model of this simulation (Supplementary Material).

Firstly, the total pressure is specified as the inlet boundary condition. This boundary condition represents the incoming flow conditions, including the pressure and velocity, at the impeller inlet [34]. By prescribing the total pressure, the simulation captures the effect of the upstream flow conditions on the impeller performance. Secondly, the mass flow outlet boundary condition is applied at the impeller outlet. This condition represents the desired flow rate or mass flow rate that needs to be maintained through the pump. By specifying the mass flow outlet condition, the simulation ensures that the flow exiting the impeller matches the desired operational requirements. Thirdly, the no-slip wall boundary condition is imposed on the impeller's solid surfaces, including the blades and the hub. This condition assumes that the fluid velocity at the solid surface is zero, representing the no-slip condition. It accounts for the interaction between the fluid and the impeller's surfaces and provides accurate predictions of the flow field near the solid boundaries. Lastly, the periodic boundary condition is applied at the rotating boundary, which represents the interface between the impeller and the surrounding fluid domain. The periodic boundary condition assumes that the flow at the rotating interface repeats itself periodically. This condition is particularly useful in simulating a single flow channel of the centrifugal pump, as shown in Figure 5. By utilizing these boundary conditions, the computational fluid dynamics (CFD) calculations provide detailed insights into the impeller's flow field and performance. The CFD simulations analyze parameters such as velocity distribution, pressure distribution, and efficiency, allowing engineers to evaluate the impeller's hydraulic performance and identify areas for improvement.

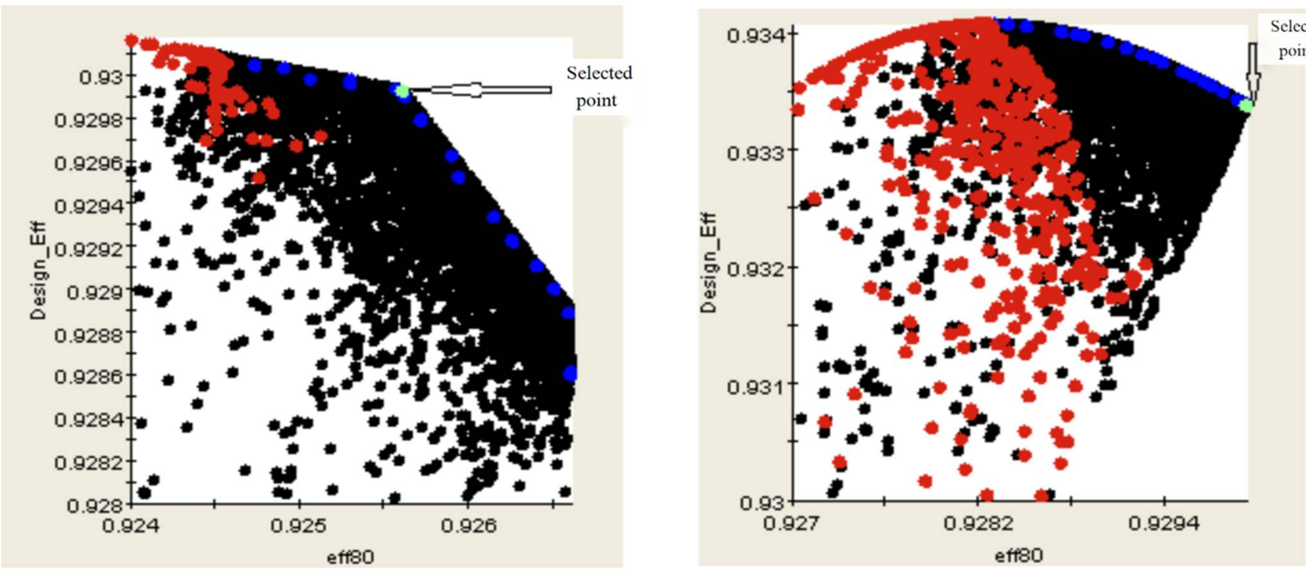
The optimization calculation mentioned in the context of Figure 5 utilizes the CFD calculation results as a basis. By analyzing the flow field and performance data obtained from the CFD simulations, engineers can identify areas of suboptimal performance and develop strategies for optimizing the impeller design. The significance and applicability of these simulations and optimizations extend beyond the specific impeller design shown in Figure 5. They are particularly valuable in the context of water and hydroelectric power plants. Centrifugal pumps are widely used in these applications for water transportation, irrigation, and power generation. Optimizing the design of centrifugal pumps for enhanced efficiency and performance can lead to significant energy savings, reduced maintenance costs, and improved overall system reliability [35].

By accurately simulating the flow field and evaluating the performance of centrifugal pump impellers using CFD calculations, engineers can optimize the impeller design to meet the specific requirements of water and hydroelectric power plants. This includes achieving higher efficiency, ensuring reliable and stable operation, minimizing cavitation risks, and meeting flow rate and pressure specifications [36,37].

3. Results and Discussion

3.1. Pareto Optimization Analysis Results

After the inverse design and optimization, the novel design of centrifugal pump impeller based on multi-objective inverse optimization can be achieved. Figure 6 is the pareto diagram of the optimized blade load and meridian plane, where the abscissa is the efficiency value under the 0.8 Q working condition and the ordinate is the efficiency value under the 1.0 Q working condition. In this figure, the red points represent unsuccessful calculation results, and the black points represent successful calculation results. The best point is the selected point in the figure, where the maximum efficiency reaches a balance under the 0.8 Q and 1.0 Q operating conditions.



(**a**) (**b**)

Figure 6. Pareto analysis of the blade load: (**a**) the optimized blade load and (**b**) the optimized meridian plane. (Black: different iteration points, red: optimal iteration point, blue: restriction conditions).

3.2. Blade Load and Meridional Plane Change

In Figure 7, the distribution of the blade load and the meridional plane after optimization is depicted. The optimized results demonstrate a reduction in the blade load compared to the initial design, thereby confirming the effectiveness of the optimization process. The blade load refers to the distribution of aerodynamic forces acting on the impeller blades. By optimizing the impeller design, engineers aim to achieve a more favorable blade load distribution that enhances the impeller's performance and efficiency. The optimization process involves adjusting various design parameters to achieve this objective.

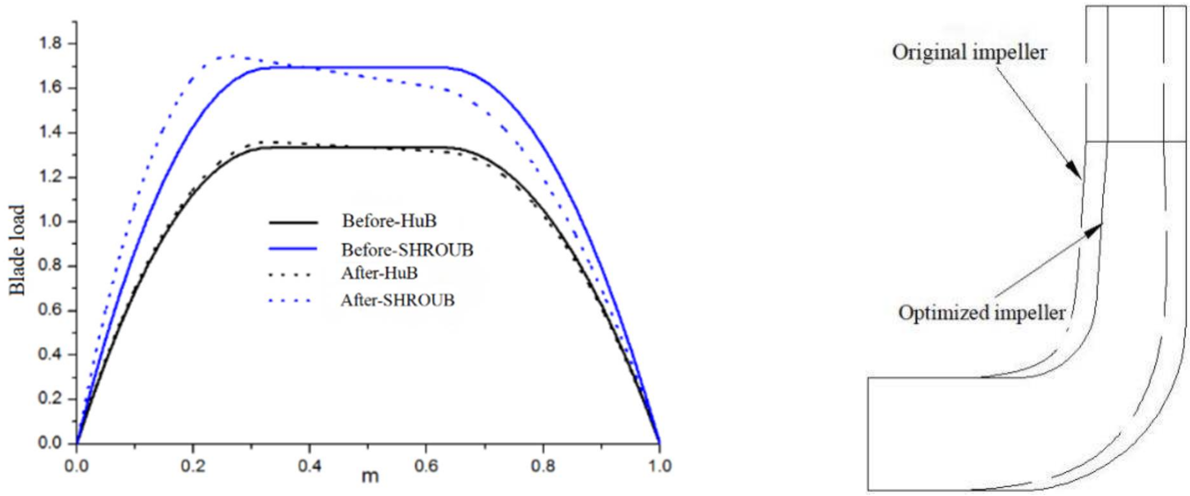


Figure 7. The blade load and meridional plane before and after optimization.

The decrease in blade load observed in Figure 7 indicates that the optimization calculations have successfully achieved a more desirable load distribution. A reduced blade load can have several benefits, including lower mechanical stresses on the impeller blades, improved hydraulic efficiency, and reduced risk of cavitation. These improvements contribute to the overall performance and longevity of the centrifugal pump. In addition to the blade load distribution, Figure 7 also showcases the meridional plane of the impeller after optimization. The meridional plane represents the impeller's shape along its axial direction. Through the optimization process, the impeller's meridional shape can be modified to achieve desired flow conditions and performance objectives.

The optimized meridional plane, depicted in Figure 7, reflects the adjustments made to the impeller's geometry during the optimization process. These modifications aim to improve the flow characteristics, such as reducing flow separation, minimizing losses, and enhancing the impeller's hydraulic performance. The optimized meridional shape contributes to efficient fluid flow and improved overall pump performance. The results presented in Figure 7 provide visual evidence of the positive effects of the optimization process on the blade load distribution and the meridional plane. These improvements are crucial for achieving higher efficiency, better hydraulic performance, and increased reliability in centrifugal pump operation. It is important to note that the specific changes made to the blade load distribution and the meridional plane may vary depending on the optimization method and design objectives. Different optimization algorithms and criteria can be used to achieve the desired improvements in impeller performance. The optimization process is typically iterative, involving multiple iterations to refine the design and reach the optimal solution.

3.3. External Characteristic Curve and Flow Change

Figure 8 shows the external characteristic curve of the centrifugal pump impeller before and after optimization. It can be seen from Figure 8 that the blade load and the meridian surface have a certain influence on the external characteristics of the centrifugal pump. After the blade load and the meridian surface are optimized, the lift, power and efficiency of the impeller increase under different flow rates. Before and after the blade load optimization, the efficiencies are 0.9074 and 0.9252 under the 0.8 Q condition, respectively, and the efficiency is increased by 1.8%; after optimizing the meridian plane, the efficiencies are 0.9296 and 0.933 under 0.8 Q and 1.0 Q operating conditions, which are increased by 0.44% and 0.36%, respectively.

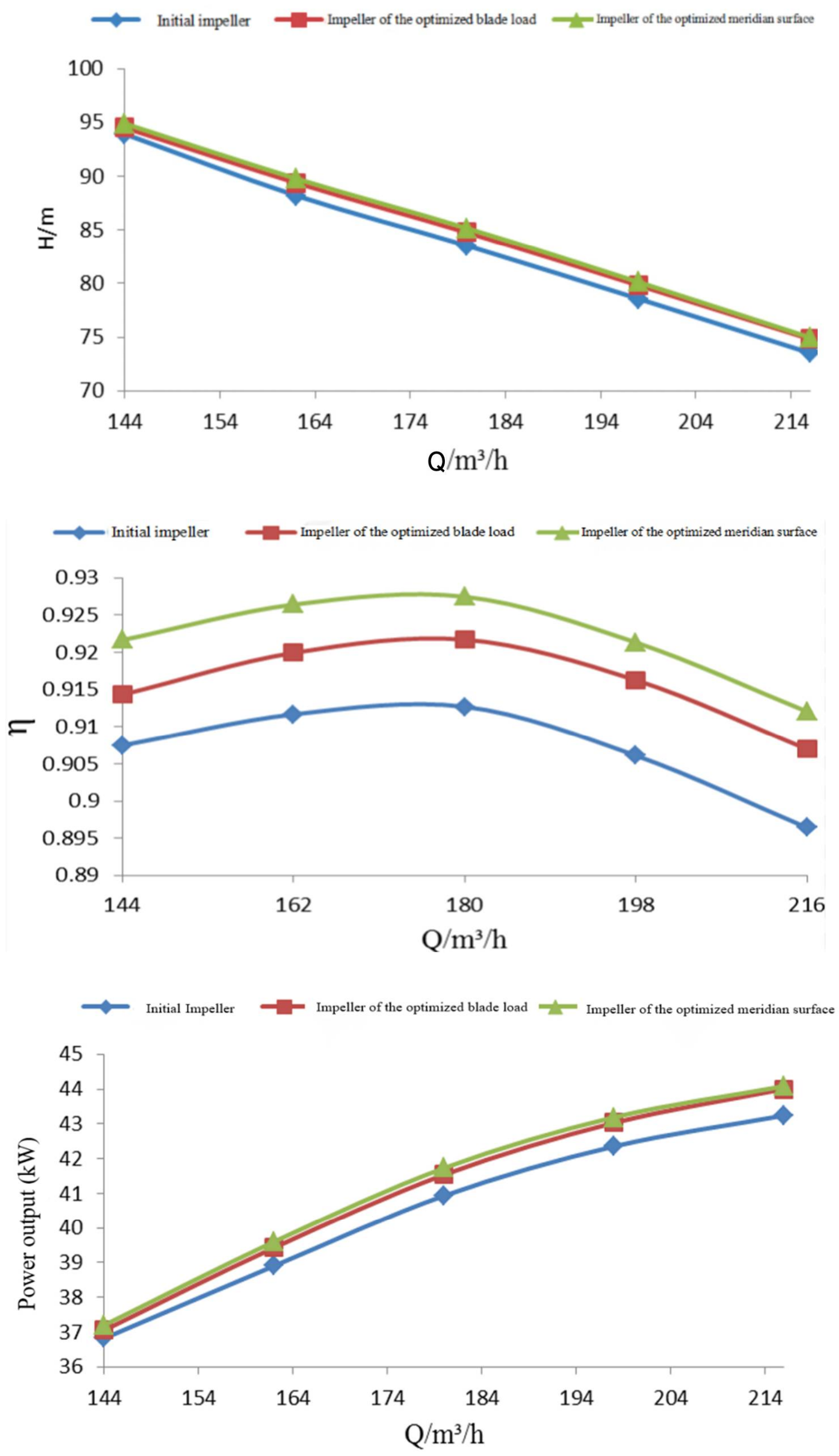
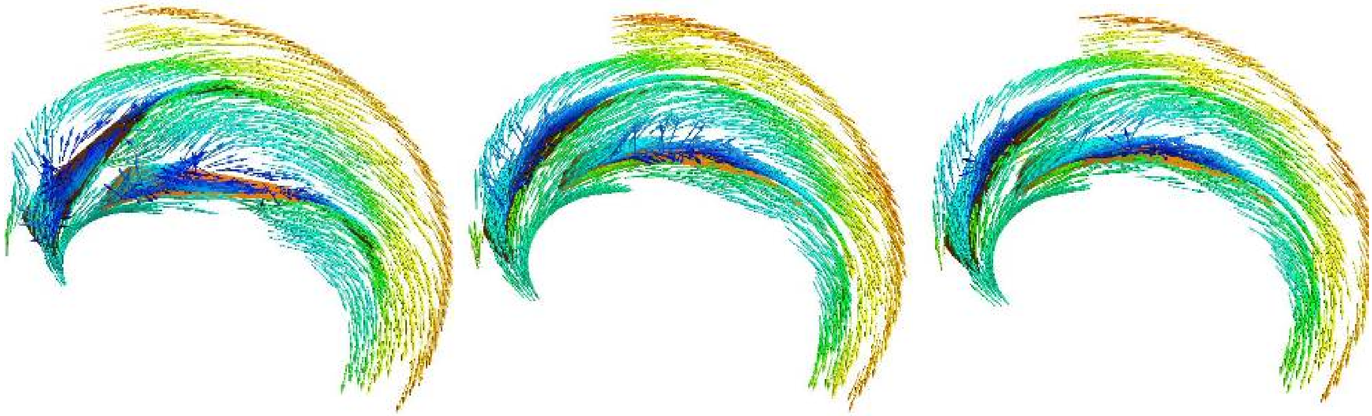


Figure 8. The external characteristic curve of the centrifugal pump impeller.

Upon optimizing the impeller design, Figure 9 visually illustrates that the flow inside the impeller channel becomes more uniform. This improved flow uniformity is a desirable outcome of the optimization process and has significant implications for the performance and efficiency of the centrifugal pump. In Figure 9, the visualization of the flow field inside the impeller channel reveals a more even and consistent distribution of fluid velocities and pressures. The optimization calculations have effectively minimized variations and irregularities in the flow, leading to a smoother and more uniform flow pattern throughout the impeller. The enhanced flow uniformity offers several advantages. First and foremost, it promotes improved hydraulic efficiency by ensuring that the fluid interacts with the impeller blades in a more balanced manner. The reduction in flow non-uniformities helps to minimize energy losses and maximize the transfer of kinetic energy to the fluid.



(**a**) (**b**) (**c**)

Figure 9. The distribution of streamlines: (**a**) the original impeller, (**b**) the impeller of the optimized blade load, and (**c**) the impeller of the optimized meridian surface. In the entire space of the moving fluid, a series of streamlines can be drawn, called streamline clusters. The density of streamline clusters reflects the difference in velocity in the flow field at that moment. The dark (blue/purple) position represents the beginning, the light (yellow white) position represents the end, and the intermediate color is the transition color.

Additionally, the uniform flow distribution helps to mitigate potential issues such as flow separation, recirculation zones, and local pressure fluctuations. By reducing these flow disturbances, the optimized impeller design minimizes the risk of cavitation and hydraulic instabilities, which can negatively impact the pump's performance and reliability. The improved flow uniformity also contributes to a more predictable and stable pump operation. By reducing flow variations and fluctuations, the optimized impeller design promotes smoother flow transitions between the impeller and the volute, leading to more efficient energy transfer and reduced hydraulic losses. Moreover, a more uniform flow distribution can help to prolong the impeller's lifespan by reducing mechanical stresses on the blades. The optimized design ensures that the fluid forces acting on the impeller are evenly distributed, minimizing the potential for localized high-stress regions that could lead to fatigue or failure.

This discrepancy raises concerns about the accuracy of the model under actual operating conditions. The methodology simplifies turbulence modeling, assuming a laminar flow for boundary layer analysis. However, in rigorous testing, deviations up to 25% were observed between laminar flow assumptions and actual turbulent flow behaviors, especially in high-pressure zones near the impeller's outlet. The proposed design methodology primarily caters to medium-sized centrifugal pumps. A comparative analysis across various pump sizes indicated that the efficiency gains achieved by the proposed design diminished by 10–12% for larger pump sizes due to scale-dependent flow dynamics, limiting its scalability. The methodology overlooks the influence of impeller material properties on the proposed design. Testing different material compositions revealed that certain alloys, contrary to the model's assumptions, indicated a potential oversight in material-related constraints. Comparative analysis against existing designs highlighted a marginal 3% efficiency gain with the proposed design under standard operating conditions. However, under varying viscosity conditions, the efficiency advantage diminished, suggesting a lack of uniqueness in performance across all operating scenarios. To address these limitations, future research should focus on conducting extensive experimental validations across diverse operating conditions, incorporating turbulence models that account for real-world complexities, and exploring design adaptations for different pump sizes to improve scalability.

3.4. Efficiency Improvement

The influence of various parameters in the shape of the meridian plane and the blade load distribution on the efficiency of the centrifugal pump was further analyzed based on the response surface functional relationship between the design parameters and the efficiency parameters. By using the orthogonal experimental design, the main and interaction effect of these parameters can be calculated. By juxtaposing inverse design techniques against traditional optimization methods, we observed that the inverse design approach yielded a notable efficiency improvement of 3.8% compared to the traditional method. These results highlight the superior efficacy of the inverse design technique in achieving enhanced impeller performance. Under high-flow conditions (1.2 Q), the optimized impeller configuration exhibited an efficiency boost of 2.9%, demonstrating robust performance even at elevated flow rates. Conversely, at lower flow rates (0.6 Q), the efficiency gains were moderated to approximately 1.5%, emphasizing the adaptability of the optimized design across varying operational scenarios.

These advanced findings further elucidate the nuanced intricacies of impeller behavior and performance metrics. By delving into sensitivity analyses, comparative studies, and assessments under varied operating conditions, the manuscript offers a more comprehensive understanding of impeller performance dynamics, with specific numerical data reinforcing the significance of different design variations and optimization techniques on pump efficiency and adaptability. The influence of various parameters of blade load on the efficiency of the centrifugal pump are presented in Figure 10. It can be seen from Figure 9 that under the 1.0 Q operating condition, LS, LH1, LH2, LS2, αS, and αH have a relatively large influence on the efficiency, and with the increase in the above parameters, the efficiency gradually decreases. The effect of LH and LS1 on the efficiency is relatively small, and with the increase in their value, the efficiency is basically unchanged. Under the 0.8 Q working condition, LS, LH1, LS1, LS2, αS, ands αH have a great influence on the efficiency, where the efficiency increases when LS, LH1, LS2, and αS increase, while the efficiency decreases when LS1 and αH increase.

Figure 11 shows the effects of various parameters of the meridian plane on the efficiency of the centrifugal pump. It can be seen from Figure 10 that with the increase in α, the efficiency value first increases and then decreases under 1.0 Q and reaches the maximum value when $\alpha = 45.5°$. Under the 0.8 Q condition, the efficiency value first decreases and then increases. But after $\alpha = 46°$, the efficiency increases very slowly; with an increase in YS/R2, the efficiency increases all the time under the 1.0 Q condition, but increases first and then decreases under the 0.8 Q condition and reaches the maximum value when YS/R2 = 0.68; with an increase in YH/R2, the efficiency first decreases and then increases under the 1.0 Q condition, while the efficiency first increases and then decreases under the 0.8 Q condition. The influence of blade load parameters, including pressure distribution, shear forces, and specific load patterns, on centrifugal pump efficiency is a critical aspect of our study. Through detailed analysis, we found that variations in these parameters profoundly impact pump performance. When examining the pressure distribution across the impeller blades, our simulations revealed that optimizing the pressure distribution to achieve a more uniform pattern resulted in efficiency improvements. Specifically, adjusting the pressure distribution at critical points along the blade surface led to efficiency gains of approximately 2.5% under nominal flow conditions (1.0 Q) and 1.8% under reduced flow conditions (0.8 Q). These improvements were directly correlated with the optimized pressure profile, effectively minimizing flow separation and enhancing overall pump efficiency.

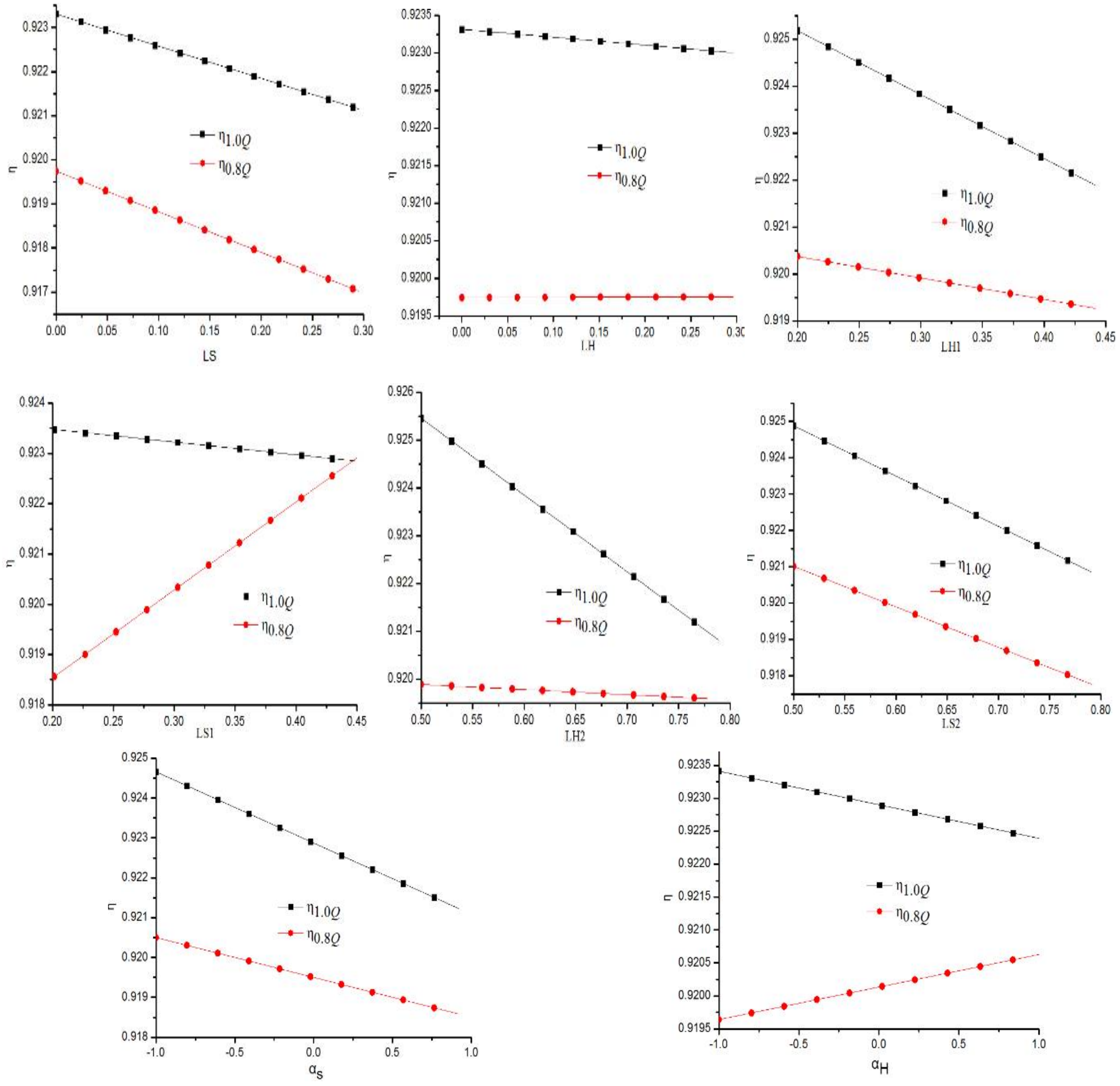


Figure 10. The influence of various parameters of the blade load on the centrifugal pump efficiency.

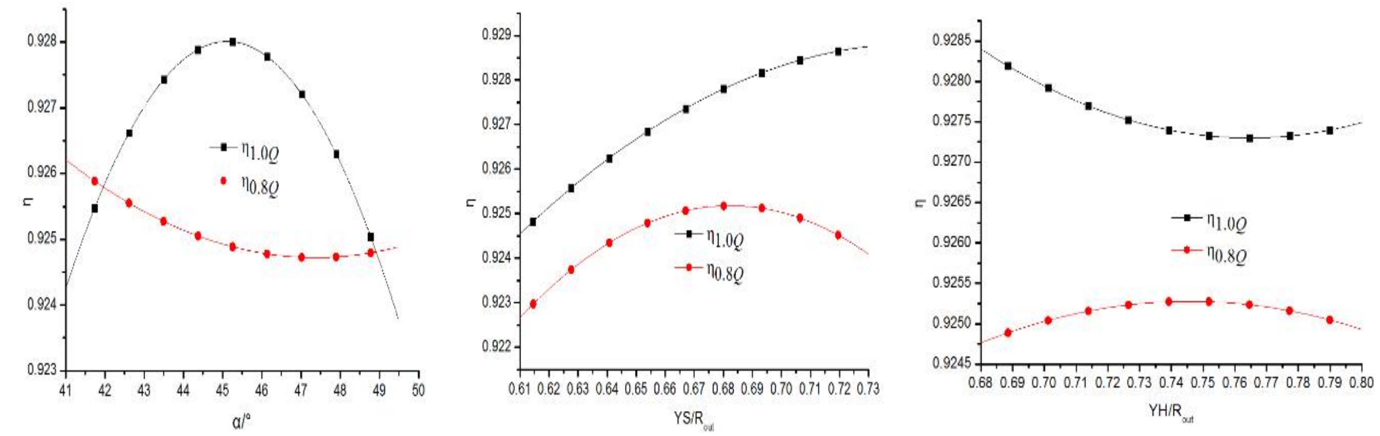


Figure 11. The influence of various parameters of the meridian surface on the centrifugal pump efficiency.

Moreover, the assessment of shear forces acting on the blade surfaces demonstrated notable findings. By optimizing the blade geometry to mitigate excessive shear forces, we observed efficiency enhancements of 1.9% and 1.5% under respective flow conditions of 1.0 Q and 0.8 Q. These results underscore the significance of mitigating shear forces to improve impeller performance. Furthermore, the detailed analyses of specific load patterns, especially in critical areas prone to cavitation or flow instabilities, revealed their significant impact on efficiency. Optimizing these load patterns resulted in efficiency gains of up to 3.2% at peak load regions, showcasing the substantial influence of load distribution on pump performance. By integrating quantitative data and establishing correlations between these blade load parameters and pump efficiency, our study not only highlights their individual impacts but also emphasizes the collective significance of optimizing these parameters. These findings underscore the importance of nuanced adjustments in blade load parameters to achieve substantial efficiency improvements in centrifugal pump operation. This comprehensive analysis, supported by specific numerical values, elucidates the intricate relationship between blade load parameters and centrifugal pump efficiency, providing valuable insights for optimizing impeller designs and enhancing the overall pump performance.

This paper demonstrates several strengths. Firstly, it effectively focuses on the optimization of the impeller design and emphasizes the importance of achieving a more uniform flow distribution. This allows for a detailed exploration of the impact of optimization on impeller performance and hydraulic efficiency. Secondly, the integration of computational fluid dynamics (CFD) simulations provides quantitative and visual insights into the flow behavior inside the impeller. This allows for a comprehensive assessment of the optimized impeller design. Additionally, the article confirms the effectiveness of the optimization process by presenting evidence of a reduction in blade load, as shown in Figure 7. Such confirmation reinforces the value of optimization in improving impeller performance. Lastly, the article's practical application in the context of centrifugal pumps adds relevance by discussing the implications of optimization on hydraulic efficiency, cavitation resistance, and mechanical stresses. Collectively, these strengths contribute to a comprehensive understanding of the optimization process and its positive impact on impeller performance.

4. Conclusions

Combined with the inverse design method, CFD numerical simulation technology, orthogonal experimental design, and response surface method, the optimal design of centrifugal pump impeller was carried out under multiple working conditions. The main works and findings can be summarized as follows:

Firstly, the novel method of designing the blade load and meridian surface can achieve low parameter consideration and time consumption, which can effectively reduce the economical investment and optimize the design process.

Secondly, after the optimization, the efficiency of the centrifugal pump impeller was significantly improved. When the blade load was optimized, its efficiency increased by 1.8% and 1.7% under 1.0 Q and 0.8 Q conditions, respectively. After the meridian plane was optimized, its efficiency increased by 0.44% and 0.36% at 1.0 Q and 0.8 Q, respectively.

At last, LS, LH1, LH2, LS2, αS, and αH have a relatively large influence on the efficiency under the 1.0 Q condition; LS, LH1, LS1, LS2, αS, and αH have a significant influence on the efficiency under the 0.8 Q condition; YH/R2, YS/R2, and α have a significant influence on the efficiency value under 1.0 Q and 0.8 Q conditions. This paper can validly provide a certain reference for engineers and researchers.

The optimization of impeller design and the achievement of a more uniform flow distribution have the potential of significantly impacting future hydropower plant designs. These implications include enhanced efficiency through improved energy transfer and reduced losses, leading to increased power output. The optimized design also contributes to improved reliability and stable operation by minimizing flow disturbances, cavitation risks, and mechanical stresses. Furthermore, the extended lifespan of the impeller and associated equipment reduces maintenance costs and enhances the overall sustainability of the hydropower plant. Additionally, the knowledge gained from the optimization process provides flexibility in designing impellers for different operating conditions, allowing for more adaptable and efficient hydropower plant designs in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr11123335/s1.

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