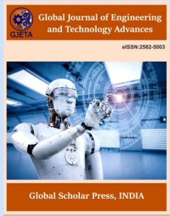
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(RESEARCH ARTICLE)

Comprehensive optimization of centrifugal pump performance through the integration of the Taguchi method and polynomial regression models

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Global Journal of Engineering and Technology Advances, 2025, 22(02), 015–026

Publication history: Received on 26 December 2024; revised on 02 February 2025; accepted on 05 February 2025

Article DOI: https://doi.org/10.30574/gjeta.2025.22.2.0026

Abstract

This study aims to optimize the performance of centrifugal pumps by integrating the Taguchi Method with polynomial regression models, and the objective is to enhance pump efficiency and reduce energy consumption by optimizing multiple design parameters concurrently; the methodology uses Design Expert 360 software and ANSYS 2024R1 to conduct experiments based on the Taguchi Method and Simulation, focusing on five factors: number of blades, impeller blade angle, flow rate, Head, and rotational speed. Computational Fluid Dynamics (CFD) simulations validated the optimization results. The optimal combination of parameters rotational speed of 1500 rpm, Head of 20 m, impeller blade angle of 36°, number of blades 6, and flow rate of 400 m^3/h achieved a maximum pump efficiency of 86.2%. The regression models developed for predicting total efficiency, Head, and shaft power showed high predictive accuracy, with R^2 values of 0.9469 for total efficiency and shaft power 0.9986 and 0.9812 for Head. CFD simulations confirmed the consistency of the optimization process with an efficiency of 84.1% and a difference of 2.1%, showing a high correlation with the optimized value. This study extends existing knowledge by employing polynomial regression models to predict pump efficiency and the Head and shaft power, providing a robust background for future design improvements in centrifugal pump performance. The findings offer valuable insights for enhancing the efficiency and performance of centrifugal pumps in various industrial applications.

Keywords: Centrifugal pump; Optimization; Taguchi Method; Polynomial regression

1. Introduction

Centrifugal pumps are indispensable in many industrial applications, such as chemical processing and water treatment, because of their dependability and efficiency. Their design factors significantly impact their performance, including Head, flow rate, rotational speed, impeller blade angle, and number of blades. Reducing energy consumption, increasing pump efficiency, and cutting operating expenses depend on parameter optimization. Low-fidelity surrogate models have been employed to reduce computational expenses and get the best answers [1]. In conjunction with particle swarm optimization, entropy generation theory has been used to reduce energy losses and boost efficiency [2]. It has been demonstrated that adaptive single-objective algorithms combined with computational fluid dynamics can automatically optimize pump shape, resulting in better internal flow fields and higher efficiency [3]. The optimization of centrifugal pump performance has been extensively researched utilizing various methods. The Taguchi strategy substantially enhances pump efficiency and overall performance when combined with numerical techniques and CFD analysis [4-6]. Impeller diameter has the most noticeable impact on pump performance, with blade angle, volute tongue angle, and impeller diameter being crucial design elements [5]). Efficiency may be increased, low-pressure areas can be reduced, and better pressure distribution can be obtained by adjusting these parameters [4]. Regression and correlation analysis have also been used to improve impeller design based on real-time data, offering an economical way to alter machinery [7].

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Extensive geometric parameter adjustment has been shown to improve centrifugal pump performance significantly, aid in a more comprehensive effective range, and raise the optimal efficiency point [4-5]. Response surface methodology (RSM) has been used to improve guide vane centrifugal pumps, considering several geometric characteristics that affect pump performance [8]. In a different work, [9] used RSM with computational fluid dynamics to forecast and maximize hydraulic efficiency for high-specific-speed centrifugal pumps. Genetic algorithms and radial basis function neural networks are two examples of multi-objective optimization approaches with concurrently enhanced centrifugal pump volutes' hydraulic and acoustic performance [10-11]) used the Taguchi approach to optimize the inlet blade and wrap angles, which improved the cavitation performance of a centrifugal pump impeller. Similarly, [12] sought to optimize design parameters such as blade outlet setting and wrap angles to increase the cavitation performance and energy conversion efficiency of ultra-low specific-speed centrifugal pumps. Using a parametric design, [13]) performed a multi-objective optimization of an ultra-high-head pump-turbine runner, highlighting the value of multi-objective optimization in attaining balanced performance gains.

By optimizing the impeller design of a centrifugal pump using the Taguchi approach, [6] discovered that this might significantly increase pump efficiency and consistency; using the Taguchi approach, [14] optimized parameters like input diameter and output breadth to increase a centrifugal pump's hydrodynamic performance. Despite their substantial contributions to the discipline, these studies frequently concentrate on optimizing individual parameters. The optimization of centrifugal pump performance using a variety of approaches has been well-studied in the past. Entropy generation theory and particle swarm optimization have improved impeller design, which has reduced entropy generation and raised efficiency [2].

A more thorough method that considers several design factors at once is required. This study combines the Taguchi Method with polynomial regression models to fill this gap and optimize a centrifugal pump's design parameters. It focuses on five factors: the number of blades, the impeller blade angle, the flow rate, the Head, and the rotating speed. This method increases the accuracy of predictions and offers a solid foundation for design enhancements.

2. Methodology

This study conducted a detailed optimization and simulation, investigating the factors affecting centrifugal pump performance, efficiency, Head, and power. The thoroughness of our methodology, from creating precise 3D geometric designs to applying realistic boundary conditions, instils confidence in the accuracy of the predictions.

2.1. Design of Experiment

This study conducted trials based on the Taguchi Method, a tried-and-true method for optimizing design components and procedures to improve quality, using the Design Expert 360 software. For the experiment design, four levels and five variables were selected. The impeller blade's operating specifications were its number of blades, angle, flow rate, Head, and rotating speed (4-7, 27-36^0, 100-400 m3/h, 20-50 m, 1500-4500 rpm). As indicated in Table 1, the experimental design used a Taguchi orthogonal array, namely L16(4^5), with five factors and sixteen runs.

2.2. Numerical Simulation

This section uses the CFD method to design, mesh, and numerically simulate an original model of a centrifugal pump based on the ANSYS 2024R1 Workbench platform Student version. This process involves creating an input-output channel. Additionally, ANSYS Computational Fluid Dynamics (CFD) was employed to model the impeller through Vista Centrifugal Pump Design (CPD), which was used to design the impeller blade.

2.3. Design Parameters

The centrifugal pump used in this study has the following operational parameters for the impeller blade: the number of blades, impeller blade angle, flow rate, Head, and rotational speed of the impeller (4-7, 27-36^0, 100-400 m^3/h, 20-50m, 1500-4500 rpm). Table 3 lists the significant elements and design parameters for the pump.

2.4. Mesh Generation

ANSYS Turbo-grid receives the model once it has been developed in Blade-Gen. This software's primary goals are complete automation and unmatched mesh quality for extremely complex blade geometries. All of the following processes are carried out automatically, and the final mesh dimensions required to produce an exceptionally high-quality mesh are specified, as shown in Figure 1 and Table 1.

Table 1 Mesh Analysis

Domain	Nodes	Elements	Statistics
R1	502250	473518	1754.85

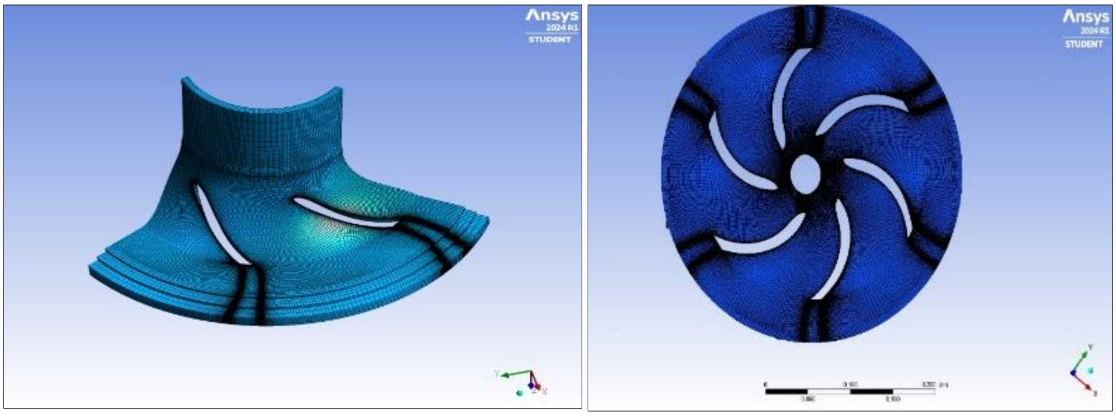

Figure 1 Mesh generation of the Optimize Impeller Blade

2.5. Boundary Conditions

The boundary conditions for the CFD simulations were set as follows:

Table 2 Boundary conditions of different blade counts

Inflow boundary condition	Mass flow inlet
Type of Fluid	Water
Turbulence Model Used	Shear Stress Transport (SST)
Flow Direction	Normal to Boundary
Reference Pressure 0 [atm]	0 [atm]
Static Pressure	1 [atm]
Mass flow rate	77.8 kg/s
Rotational Speed	1500 rpm,
Wall roughness	Smooth Wall
Wall influence on the flow	No Slip
Turbulence intensity	5%

The centrifugal pumps' CFD simulations' boundary conditions centre on varying impeller blade counts, with a mass flow rate of 77.8 kg/s; water serves as the working fluid. Using the Shear Stress Transport (SST) turbulence model, the simulations average the flow direction at the boundary. One bar is the static pressure, while zero is the reference pressure. 1500 rpm is the impeller's rotational speed. Smooth surface roughness and a no-slip condition are imposed on the walls. As seen in Table 2, the turbulence intensity is set at 5%.

2.6. Governing Equations

The efficiency of the pump (η) Furthermore, one crucial aim function for immediate optimization in the specified pumps was the Net Positive Suction Head (NPSH) [15], which outlines the optimal centrifugal pump's efficiency.

$$H = \frac{P_d - P_s}{\rho g} \text{ – } 1,$$

$$\eta = \frac{P_{in}}{P_{out}} \text{ – } 2,$$

$$P_{out} = \rho \times g \times H \times Q \text{ – } 3,$$

The inlet pressure is denoted as P_{in}, while specifically unsolidified mass and charge velocity are denoted as Y and v_{in}, respectively. Q represents the flow rate.

2.7. Orthogonal Optimization

Table 3 presents the design of the orthogonal array.

Table 3 Design of Orthogonal Array

Run	Rotational Speed (rpm)	Head (m)	Impeller blade angle (^{0})	Number of blades	Flow rate (m^3/h)
1	4500	50	27	6	200
2	3500	40	27	5	400
3	2500	50	33	5	100
4	1500	50	36	7	400
5	1500	20	27	4	100
6	3500	50	30	4	300
7	1500	40	33	6	300
8	4500	20	36	5	300
9	3500	30	36	6	100
10	2500	40	36	4	200
11	4500	40	30	7	100
12	1500	30	30	5	200
13	3500	20	33	7	200
14	4500	30	33	4	400
15	2500	30	27	7	300
16	2500	20	30	6	400

Table 4 represents the pump efficiency, shaft power, and Head of the numerical simulation results of the orthogonal design.

Table 4 Numerical Results of the orthogonal design.

Run	Pump Efficiency (%)	Shaft Power (Kw)	Head (m)
1	88	33.9	39
2	73.9	48.8	47
3	36.5	7.8	3.7
4	91	3.5	41

5	68	4.3	4
6	80.5	53	56
7	87.5	1.8	21
8	89.7	35.1	41
9	77.5	10.2	10
10	87.6	25.5	29
11	60.5	10.4	8
12	85	10.6	12
13	88.7	16.1	19
14	80.3	46	48
15	81.3	26.4	28
16	82.8	32	34

3. Results

3.1. Optimization Results

The optimization focused on five key parameters: rotational speed, head, impeller blade angle, number of blades, and flow rate. Tables 5 and 6 summarize the optimal values for these parameters.

Table 5 Presents the optimization results for the impeller blade parameters and the solution for the four-factor levels of the optimization results.

Number	Rotational Speed	Head	Impeller blade angle	Number of blades	Flow rate	Pump efficiency	Power (Kw)	Desirability	
1	**1,500**	***20***	***36***	***6***	**400**	**86.202**	**22.837**	**0.518**	**Selected**
2	3,500	*20*	*36*	*6*	400	83.474	22.837	0.508	
3	4,500	*20*	*36*	*6*	400	82.949	22.837	0.506	
4	2,500	*20*	*36*	*6*	400	75.374	22.837	0.477	

The optimal combination of parameters for maximum pump efficiency was selected at a rotational speed of 1500 rpm, Head of 20 m, impeller blade angle of 36°, number of blades 6, and flow rate of 400 m^3/h, achieving an efficiency of 86.2% of the optimized parameters.

3.2. Confirmation Test

The optimal impeller blade parameters were confirmed through additional tests. The results are presented in Table 6.

Table 6 Confirmation of the Optimal Impeller Blade.

Rotational Speed(rpm)	Head(m)	Impeller blade angle (^{0})	Number of blades	Flow rate(m3/h)
1,500	20	36	6	400

3.3. CFD Simulation Validation

CFD simulations were conducted to validate the optimization results. The optimal blade's Head, 26.3 m, total efficiency, 84.05%, and shaft power, 23.8 KW, were calculated by varying the mass flow rates. The results are summarized in Table 7.

Table 7 CFD Calculation of the Head, Total efficiency, and Shaft power of the Optimal blade by varying mass flow rates.

Mass flow rate (kg/s)	Head (m)	Efficiency (%)	Shaft Power (KW)
77.8	26.2566	84.0514	23.834
80	26.0805	84.1995	24.301
90	25.1503	85.2545	26.037
100	23.8471	85.8339	27.247
110	23.7713	89.7573	28.571
120	22.7436	91.4167	29.279
130	21.7318	91.9182	30.141

The velocity vectors at the impeller blade's 20%, 50%, and 80% span are displayed. Near the leading edge of the impeller blade, at 20% span, the lowest velocity is shown, signifying the fluid's first acceleration. At this span, where the fluid gathers momentum from the impeller's spin, Figure 2 displays the most incredible velocity close to the trailing edge. The velocity distribution gets more complicated around 50% span, with greater velocities localized close to the blade surfaces. While the maximum velocity dramatically rises, suggesting effective energy transfer, the lowest velocity stays close to the leading edge. With the most considerable velocity occurring close to the blade tips, the velocity vectors at 80% span demonstrate a well-distributed flow pattern, indicating efficient fluid management across the blade span.

The total pressure (Ptr), static pressure (Ps), and total pressure (Pt) contour plots at 50% span are shown in Figure 3. Effective energy transmission is shown by the lowest total pressure (Ptr) at the intake and the highest total pressure close to the blade surfaces. With the lowest static pressure at the intake and the highest at the outlet, the pressure (Ps) contour ensures a constant flow rate by gradually increasing from the inlet to the exit. The locations of maximum pressure, which correspond to those with the best energy conversion efficiency, are highlighted by the total pressure (Pt) contour. The outcomes confirm how well the revised impeller design provides consistent pressure distribution, lowers hydraulic losses, and boosts pump efficiency.

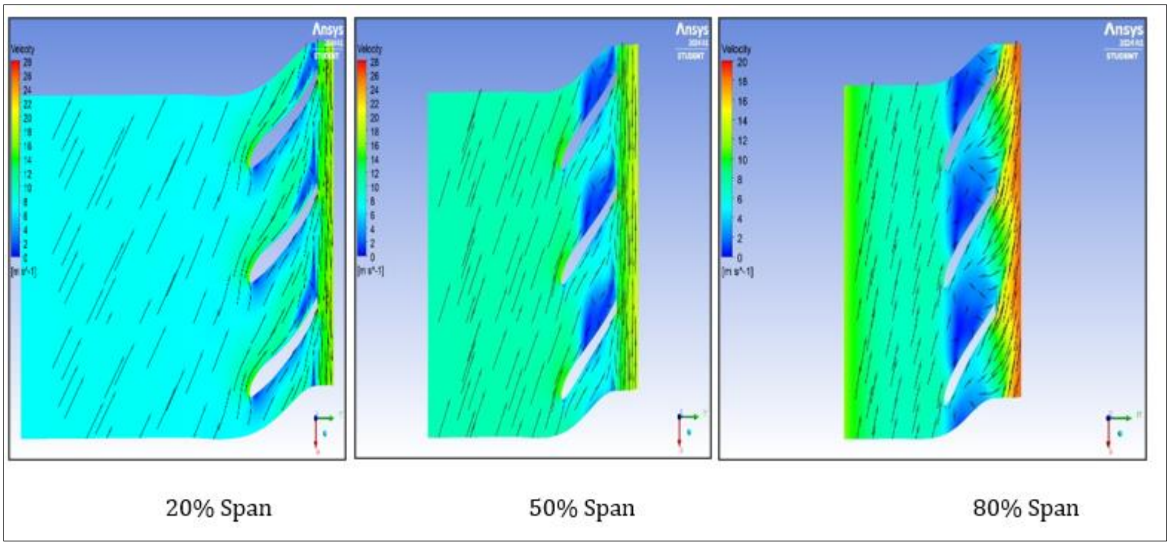

Figure 2 Velocity Vectors at 20%, 50% Span and at 80% Span

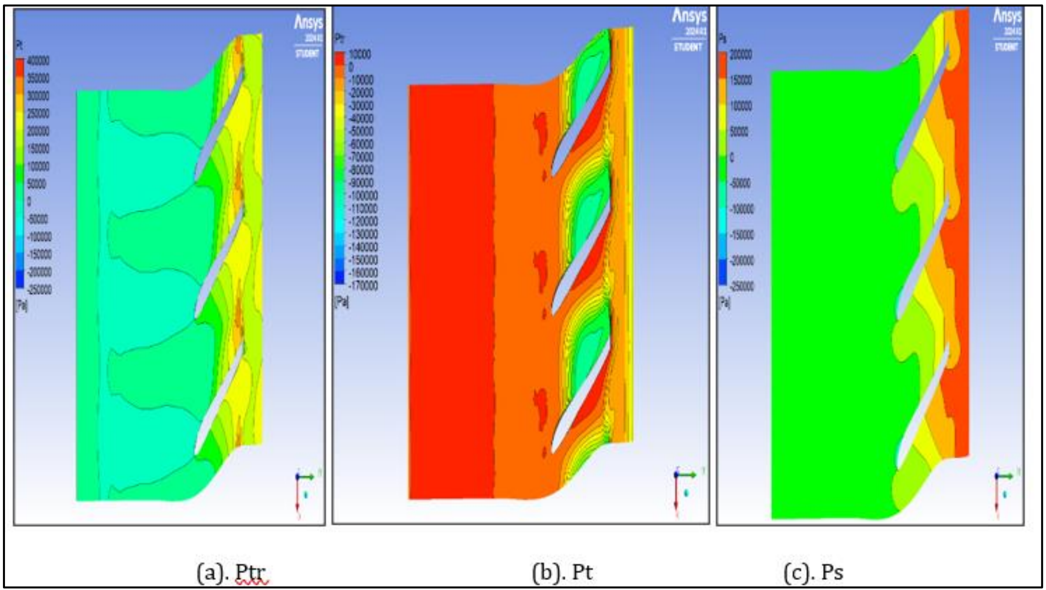

Figure 3 The contour of P tr, Pt and Ps at 50% span

3.4. Regression Models

The regression polynomial equations for total efficiency, shaft power, and Head with mass flow rate are as follows:

Table 8 Coefficient of ṁ², ṁ, R^2 and the Predicted values Regression Model of Total Efficiency

ṁ (kg/s)	Coefficient of ṁ²	Coefficient of ṁ	Predicted Efficiency (%)	Constant
77.8	3.63	3.11	83.65	76.911
80.0	3.84	3.20	83.95	76.911
90.0	4.86	3.60	86.37	76.911
100.0	6.0	4.00	86.91	76.911
110.0	7.26	4.40	88.57	76.911
120.0	8.64	4.80	90.35	76.911
130.0	10.14	5.2	92.25	76.911
$(\eta)_{efficiency} = 0.0006\dot{m}^2 + 0.04\dot{m} + 76.911, \quad R^2 = 0.9469$				

Table 9 Coefficient of ṁ², ṁ, R, ²Predicted values, Head's regression model.

Mas flow rate ṁ (kg/s)	Coefficient of ṁ²	Coefficient of ṁ	Predicted Head (m)	Constant
77.8	1.211	-9.033	26.49	34.322
80.0	1.280	-9.288	26.31	34.322
90.0	1.620	-10.449	25.49	34.322
100.0	2.000	-11.61	24.71	34.322
110.0	2.420	-12.771	23.97	34.322
120.0	2.880	13.932	23.27	34.322
130.0	3.380	-15.093	22.61	34.322
$Head = 0.0002\dot{m}^2 - 0.1161\dot{m} + 34.322, \quad R^2 = 0.9812$				

Table 10 Coefficient of $\dot{m}^2$, $\dot{m}$, R^2 and the Predicted values Regression Model of Shaft Power

Mass flow rate ṁ (kg/s)	Coefficient of $\dot{m}^2$	Coefficient of ṁ	Predicted Shaft Power P (KW)	Constant
77.8	-7.26	28.76	23.94	24437
80.0	-7.68	29.58	24.34	24437
90.0	-9.72	33.27	25.99	24437
100.0	-12.0	36.97	27.41	24437
110.0	-14-52	40.67	28.59	24437
120.0	-17.28	44.36	28.76	24437
130.0	-20.28	48.06	30.22	24437
$P_{shaft} = -0.0012\dot{m}^2 + 0.3697\dot{m} + 24437, \quad R^2 = 0.9986$				

Tables 8, 9, and 10 show the regression models forecasting the centrifugal pump shaft power, Head, and overall efficiency. With an R2 value of 0.9469, the overall efficiency model (Table 8) exhibits great prediction accuracy and matches the data well. Although significantly lower, the head model, as shown in Table 19, still reflects a perfect match with an R^2 value of 0.9812. A high R^2 value of 0.9986 was also validated by the shaft power model, described in Table 10, demonstrating its predictive solid abilities. The shaft power and overall efficiency models are the best of the three since they have the greatest and identical R2 values, indicating a more fantastic ability to predict the respective precise centrifugal pump performance measuring system.

The overall efficiency equation is displayed in Figure 4 and has a high predicted accuracy and a great fit, as indicated by its R^2 value of 0.9986. As the graph shows, efficiency rises with mass flow rate, reaching an ultimate at higher flow rates. The shaft power equation is shown in Figure 5 and has a high connection with an R^2 value of 0.9986. Because more energy is needed to sustain more excellent flow rates, the graphic shows that shaft power rises with mass flow rate. The head equation is shown in Figure 6, where a perfect fit is shown by an R^2 value of 0.9812. The graph shows the trade-off between flow rate and pressure head by showing that the Head marginally lowers as the mass flow rate increases.

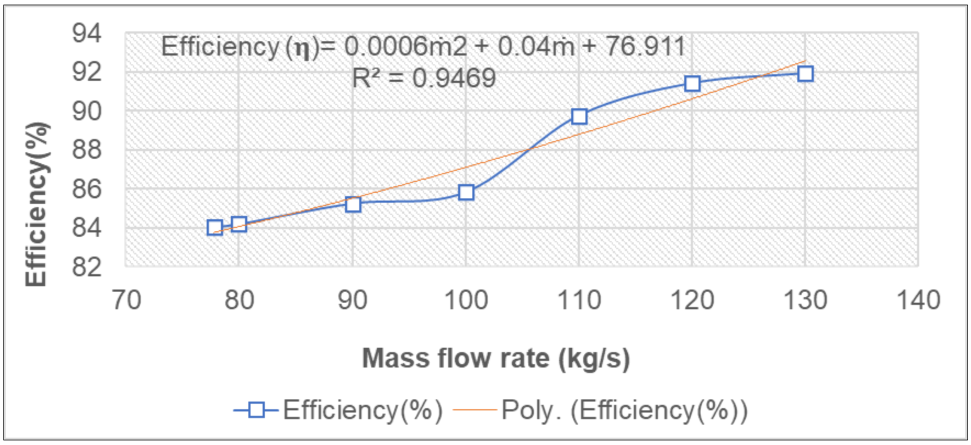

Figure 4 Regression polynomial equation for efficiency for the optimal blade

$$(\eta)_{efficiency} = 0.0006\dot{m}^2 + 0.04\dot{m} + 76.911, \quad R^2 = 0.9469 - - - - - - - - 4,$$

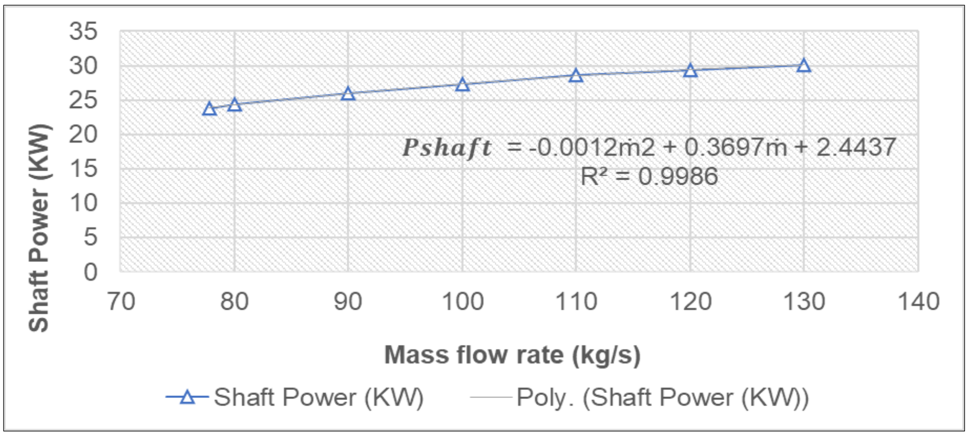

Figure 5 The regression equation for shaft power for the optimal blades

$$\boldsymbol{P_{shaft} = -0.0012\dot{m}^2 + 0.3697\dot{m} + 2.4437} ------------------ \mathbf{5},$$

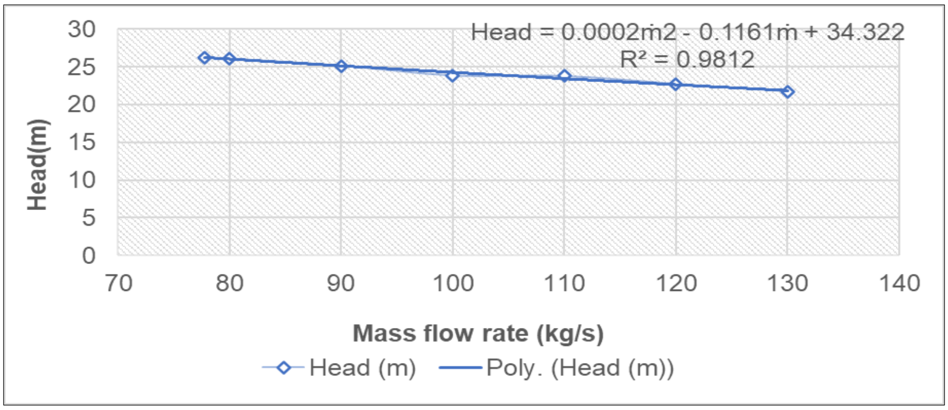

Figure 6 Regression polynomial equation for the Head for the Optimal blades

$$Head = 0.0002\dot{m}^2 - 0.1161\dot{m} + 34.322 ------------------ 6,$$

Evaluate the effectiveness of the ideal impeller blade at different mass flow rates by contrasting the regression model's predictions with the CFD simulation results. A high degree of accuracy in the regression model is indicated by Figure 7, which displays a close alignment between the CFD results and the regression model predictions. As the mass flow rate rises, the efficiency peaks and modestly decreases at the most significant flow rates. According to this tendency, an improved impeller blade design may efficiently increase efficiency up to a point beyond which the gains in efficiency start to decline. The strong correlation between the CFD and regression model findings confirms the polynomial regression model's accuracy in predicting pump efficiency, demonstrating its resilience and usefulness in maximizing centrifugal pump performance.

The graph indicates that both approaches forecast a declining trend in the Head when the mass flow rate rises. Especially at higher flow rates, the regression model somewhat overestimates the Head compared to the CFD findings. According to this, the regression model may need to adequately represent the intricacies of fluid dynamics at more excellent flow rates, even though it is typically accurate, as shown in Figure 8. Figure 9 contrasts the shaft power of the ideal blade over a range of mass flow rates as predicted by CFD simulations and regression models; with increased mass flow rates, both approaches exhibit a rising trend in shaft power. A small quantity of the regression model underestimates the shaft power compared to the CFD results, particularly at higher flow rates.

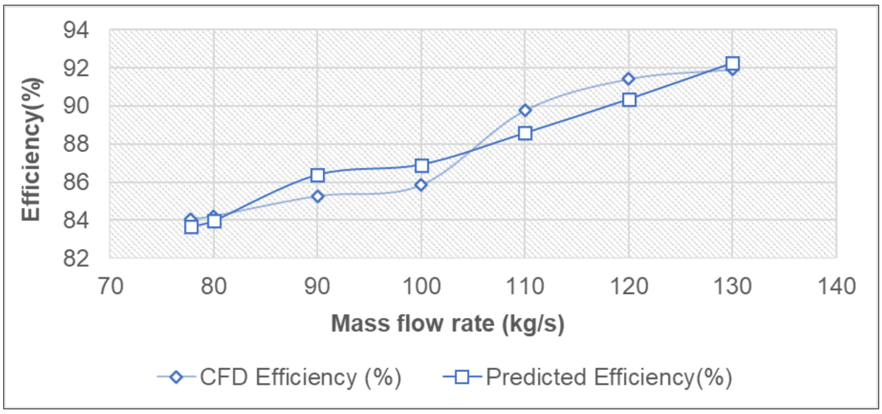

Figure 7 A comparison of CFD and predicted efficiency for the optimal blades

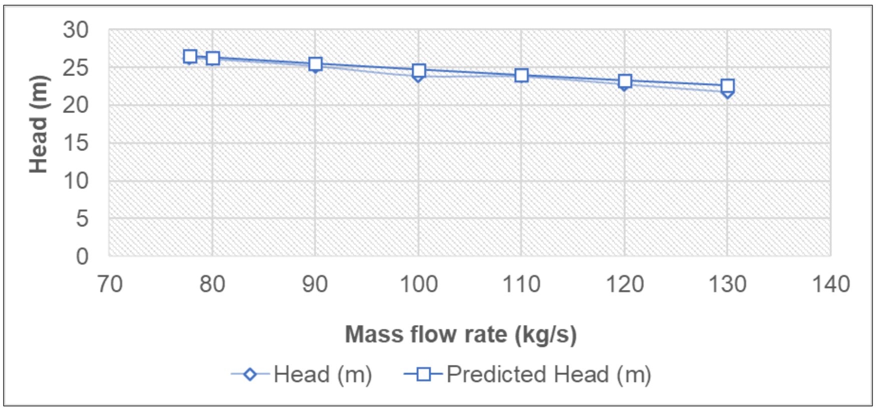

Figure 8 A comparison of CFD and Predicted Head for the Optimal Blade

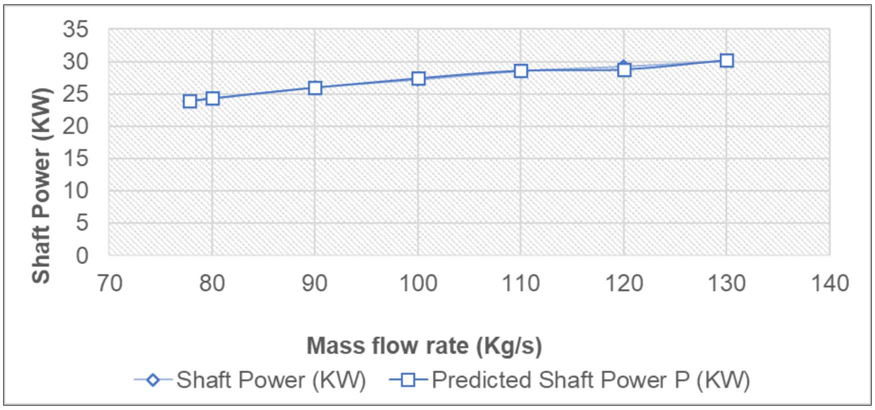

Figure 9 Comparison of CFD and Predicted shaft power for optimized Blade

4. Discussion

The optimization of centrifugal pump performance using the Taguchi Method and polynomial regression models has yielded significant efficiency improvements. The optimal combination of parameters rotational speed of 1500 rpm, Head of 20 m, impeller blade angle of 36°, number of blades 6, and flow rate of 400 m^3/h resulted in a maximum pump efficiency of 86.2%. The blade angle determines the fluid's flow direction and velocity, whilst the number of blades affects flow distribution and pressure head. A 36° blade angle balances fluid acceleration and pressure build-up, reducing energy losses caused by turbulence and flow separation.

The 400 m^3/h flow rate and rotational speed of 1500 rpm were optimal for achieving high efficiency. The flow rate determines the fluid volume the pump handles, while the rotational speed affects the kinetic energy imparted to the fluid. At 1500 rpm, the impeller imparts sufficient energy to the fluid to achieve the desired Head without causing excessive turbulence or cavitation. According to Bernoulli's principle, an increase in the fluid's speed co-occurs with a decrease in pressure or potential energy. The optimized impeller design maximizes the fluid velocity while maintaining a stable pressure distribution, leading to higher efficiency. Euler's pump equation relates the Head developed by the pump to the impeller's rotational speed and the fluid's tangential velocity. The optimized parameters align with Euler's equation, ensuring that the energy transfer from the impeller to the fluid is maximized, resulting in higher Head and efficiency.

The regression models have good prediction accuracy. R^2 values of 0.9469 for efficiency, 0.9986 for shaft power, and 0.9812 for Head further validate the optimization process. The close alignment between the CFD simulation results and the regression model predictions indicates the robustness of the optimization method. The CFD simulations confirmed the optimization results, with the optimal blade achieving a head of 26.3 m, efficiency of 84.05%, and shaft power of 23.8 KW. The slight difference between optimization and simulated values of 2.1% demonstrates the high accuracy of the optimization.

The pressure and velocity distribution plots in Figures 3 and 4 show a well-distributed flow pattern across the blade span, indicating efficient fluid management. The total pressure contour highlights effective energy transmission, while the static pressure contour ensures a constant flow rate.

To improve cavitation performance and energy efficiency, [11-12] used the Taguchi method to optimize specific centrifugal pump parameters, such as the inlet blade angle and wrap angle. This study uses the Taguchi method to optimize several design parameters, including the impeller blade angle, number of blades, flow rate, Head, and rotational speed. To enhance hydrodynamic performance,[14] improved parameters such as outlet width and inlet diameter, whereas Nataraj and Arunachalam [6] concentrated on improving impeller shape. This study expands on this methodology by concurrently optimizing various factors. This thorough optimization goes beyond the objective of earlier research, which was to improve pump performance by considering several interrelated elements. In line with the current findings,[13] confirmed that multi-objective optimization could improve balanced performance in pump-turbine runners. The optimal combination of parameters achieved an efficiency of 86.2%, and CFD simulation validated the optimal blade efficiency of 84.1%. These findings validate significant improvements in pump efficiency.

5. Conclusion

This study effectively supports the efficacy of combining the Taguchi Method with polynomial regression models for optimizing centrifugal pumps. The thorough methodology employed in this study addresses the limitations of earlier research that concentrated on maximizing individual factors alone. This study offers a strong foundation for improving pump performance by considering several design characteristics simultaneously.

The ideal design characteristics were a rotating speed of 1500 rpm, a head of 20 m, an impeller blade angle of 36°, six blades, and a 400 m^3/h flow rate. This combination achieved the most incredible pump efficiency of 86.2%.

The regression models developed for predicting the centrifugal pump's total efficiency, Head, and shaft power showed high predictive accuracy, with R^2 values of 0.9986 for total efficiency and shaft power and 0.9812 for Head. These models provide a dependable tool for predicting pump performance under various operational conditions. Future research could explore integrating other optimization techniques with polynomial regression models to improve predictive accuracy and robustness.

Data Availability Statement

The authors will provide the underlying data supporting this article's conclusions without excessive restrictions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Funding

Funding for the work was sponsored by the Petroleum Technology Development Fund (PTDF) in Abuja, Nigeria.

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