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Article

Design optimization of a domestic centrifugal pump using Taguchi Method

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Abstract. This study focuses on optimizing the design of a domestic centrifugal pump through the Taguchi method, aiming to enhance its performance. Experimental data on pump performance, including total head, efficiency, and suction specific speed, were collected and analyzed. The effects of three design parameters—impeller diameter, blade angle, and volute tongue angle—were investigated using ANOVA. The analysis revealed that impeller diameter had the most significant influence on pump performance, followed by volute tongue angle and blade angle. Optimal performance was achieved with a 55 mm impeller diameter, 25° blade angle, and 20° volute tongue angle. These findings provide valuable insights for engineers seeking to improve centrifugal pump performance, highlighting the importance of impeller diameter in particular. By optimizing design parameters, significant enhancements in pump performance can be achieved, leading to more efficient and effective domestic centrifugal pumps.

Keywords: centrifugal pump, Taguchi method, design optimization, impeller diameter, pump performance, volute tongue angle, blade angle, ANOVA analysis.

1. Introduction

In both industrial and civil applications, the centrifugal pump is a commonly utilized tool. Given that improving efficiency leads to decreased energy consumption and lower operating costs, it has traditionally been the primary goal in optimizing the design of centrifugal pumps [1, 2].

Achieving optimal performance in centrifugal pump design mandates a nuanced consideration of multiple interconnected design parameters. Parameters such as impeller diameter, blade angle, and volute tongue angle play pivotal roles in shaping the pump's functionality and performance characteristics [3].

Centrifugal pump provides pressure at the outlet by converting mechanical energy from the rotor, generally motor, to the fluid which enters the impeller that is rotated by motor. Fluid is sucked by impeller center and enters through the inlet and is being thrown out radially along impeller blades, as shown on Figure 1 [4].

Centrifugal force generated by rotation thus increases fluid velocity which in terms is converted to pressure at the outlet [5].

The delicate interplay of these factors underscores the complexity inherent in designing centrifugal pumps that meet or exceed desired performance criteria.

Despite extensive research on the subject, there remain certain unexplored and unidentified issues. The primary focus of much of this research lies in the geometry of pumps, particularly the impeller geometry, as it constitutes the dynamic component responsible for converting rotational energy into kinetic energy and transferring it to the fluid. Alterations in impeller geometry can result in adjustments to the velocity triangles of the fluid as it flows through, potentially enhancing the pump's performance.

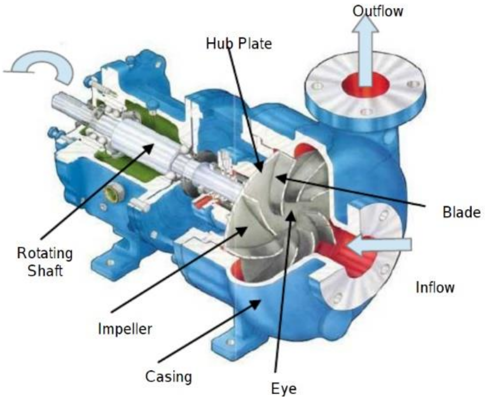

Figure 1 – Main components of a centrifugal pump

Performance metrics such as total head, efficiency, and suction-specific speed play a crucial role in gauging the success of centrifugal pump designs [7]. With industries constantly striving to boost efficiency, lower energy usage, and extend the life of equipment, optimizing centrifugal pump designs has become a crucial task.

In this study, we explore the intricate development of a domestic centrifugal pump, recognizing its significant influence on our daily lives. Despite its common presence, this pump serves as a representative of larger technological progress. By utilizing advanced methods, our goal is to improve and elevate its performance, ultimately aiding in the effectiveness and dependability of essential tasks such as water supply and irrigation. As we delve into the complex terrain of design optimization, our trusty guide is none other than the Taguchi method. Genichi Taguchi's invention known as the Taguchi method is a mathematical method for obtaining an optimal system. Taguchi Method, developed by Genichi Taguchi, is a statistical approach to optimization that aims to improve the quality and performance of products and processes while minimizing variation and cost. It is widely used in engineering and manufacturing industries for design optimization, process improvement, and robustness analysis. The L9 orthogonal array (OA) is a specific experimental design matrix commonly used in Taguchi experiments. An orthogonal array is a structured matrix that allows for a systematic and efficient experimentation process by reducing the number of experimental runs required to evaluate multiple factors and their interactions. The L9 OA is particularly useful when dealing with a small number of factors or variables. It consists of nine experimental runs, each corresponding to a combination of factor levels. Despite the small number of experimental runs, the L9 OA enables the identification of main effects and some two-way interactions among factors.

Its interest lies in its efficiency in guiding the design, even when a number of tests are restricted. This approach involves assigning levels to factors, or design elements, and using orthogonal arrays to conduct analyses appropriately. Renowned for its reliability and effectiveness, this optimization technique [8] offers a systematic approach to pinpointing the ideal combination of design parameters. By utilizing this method in our domestic centrifugal pump design, our goal is twofold: to boost operational efficiency and gain valuable knowledge that could have implications across various applications of centrifugal pumps. This study integrates engineering precision with practical application, aiming to bridge theoretical design concepts with tangible improvements in centrifugal pump functionality. By exploring the utilization of the Taguchi method in domestic centrifugal pump development, our goal is to contribute to improved effectiveness, reduced energy consumption, and prolonged lifespan, potentially impacting both household and industrial applications.

2. Methods

This study employs an experimental research design to investigate methods for optimizing a centrifugal pump for domestic use. Through the establishment of a controlled environment, experimental studies enable the intentional manipulation of variables to systematically observe their effects. In this particular project, we will be altering key design parameters such as impeller diameter, blade angle, and volute tongue angle to gauge their impact on the pump's functionality and performance qualities. Our decision to utilize an experimental approach stems from the need to gather empirical data on how these design parameters influence the pump's performance. Through deliberately varying these parameters, we strive to gain a comprehensive understanding of their individual and collective effects on the pump, ultimately leading to overall design optimization.

In this study, the term "participants" denotes the simulated centrifugal pump prototypes, which were generated and managed within a computer simulation environment employing sophisticated computational fluid dynamics (CFD) tools. The ANSYS Fluent software, in particular, played a central role in the analysis [9]. These digital prototypes were used to represent the design of a domestic centrifugal pump. To acquire insights into virtual pump design, we utilized a comprehensive CFD software for our simulation experiments. Within this simulation environment, we systematically altered key design elements such as impeller diameter, blade angle, and volute tongue angle, while recording performance data at specific intervals. These recorded results offer a clear understanding of how virtual pump prototypes respond to different design variables. To ensure the accuracy and reliability of our data, we primarily utilized ANSYS Fluent, a robust CFD software. We carefully adjusted this software to produce results that are both accurate and consistent, as documented by Matsson in 2022 [10]. Additional assurance was provided through data validation checks performed within the software interface, ensuring the precision and consistency of all simulated performance metrics.

Within these simulations, we examined the impact of various design parameters, such as impeller diameter, blade angle, and volute tongue angle, which served as our independent variables. These parameters were then evaluated against several dependent variables, specifically pump performance metrics, including total head, efficiency, and suction-specific speed.

The simulation software automatically collected data throughout the experiment, enabling constant tracking of performance metrics as the design parameters were manipulated. Due to the reliance on computer simulations, control groups were not utilized in this study. The primary objective was to enhance the design parameters of the simulated pump prototypes using the ANSYS Fluent CFD environment, highlighting its notable capabilities.

Data analysis was performed using the Taguchi method, a widely recognized statistical approach commonly employed in studies centered on design optimization [8]. The implementation occurred within a computer simulation environment, leveraging the capabilities of ANSYS Fluent. The simulation allowed systematic analysis for the best combination of design parameters. The signal-to-noise (S/N) ratio for each run was calculated to assess performance, drawing from established methodologies in experimental design [11]. Analysis of variance (ANOVA) was used to assess the significance of the design parameters, following established statistical practices [12].

The end-suction centrifugal pump being examined is a staple in domestic and agricultural settings due to its representative traits [13]. Table 1 shows characteristics of end-suction centrifugal pump. Made of durable stainless steel, this particular pump features an impeller, wear ring, pump cover and bracket. Its design renders it particularly suitable for investigating the effects of various parameters on its performance.

Table 1 – End-suction centrifugal pump characteristics

Parameters	Values
Nominal diameter (DN)	80 to 400
Flow rate	Up to 1800 m^3/h
Head	Up to 220 m
Pressure	Up to 25 bar
Temperature	Up to 150°C
Motor	Standard and EX motors
Applications	Water, water with additives, seawater and oils up to 500 cSt

2.1 Selection of Design Parameters:

When designing a centrifugal pump, careful consideration is given to the impeller diameter, blade angle, and volute tongue angle. These design parameters are known to have a significant impact on the functionality of the pump, as established by past research [14]. By systematically varying these parameters, a comprehensive analysis can be conducted to fully understand their effects on pump performance.

2.2 Experimental Design Matrix:

Table 2 presents the experimental design matrix for this study. Each row corresponds to a unique combination of impeller diameter, blade angle, and volute tongue angle. The matrix is constructed using an orthogonal array to ensure a balanced and efficient exploration of the design space. The selected matrix facilitates the identification of optimal design parameters.

Table 2 – Design matrix for L9 orthogonal array

Run	Impeller Diameter (mm)	Blade Angle (°)	Volute Tongue Angle (°)
1	50	20	10
2	50	25	20
3	50	30	30
4	55	20	20
5	55	25	30
6	55	30	10
7	60	20	30
8	60	25	10
9	60	30	20

3. Results and Discussion

The experimental results obtained for the pump performance are shown in Table 3. The results were analyzed using the ANOVA to determine the significance of the design parameters and their interactions on the pump performance.

Table 3 – Experimental results for pump performance

Run	Impeller Diameter (mm)	Blade Angle (°)	Volute Tongue Angle (°)	Total Head (m)	Efficiency (%)	Suction Specific Speed
1	50	20	15	18.3	54.6	1.65
2	50	25	20	17.5	51.2	1.91
3	50	30	25	16.4	48.9	2.26
4	55	20	20	19.6	58.3	1.58
5	55	25	15	21.5	61.5	1.40
6	55	30	20	20.1	59.1	1.70
7	60	20	25	18.1	53.2	1.86
8	60	25	15	22.2	63.2	1.34
9	60	30	20	19.7	58.8	1.64

3.1 Impeller Diameter:

Examining the variations in impeller diameter, it becomes evident that larger diameters generally correspond to higher values of total head and efficiency. This aligns with the expected behavior, as increased impeller diameter typically leads to enhanced pump performance. The most notable increase is observed in Run 8, where a 60 mm impeller diameter resulted in a substantial improvement in both total head (22.2 m) and efficiency (63.2%).

Khoeini et al. observed a similar trend where larger impeller diameters corresponded to enhanced pump performance, particularly in terms of total head and efficiency. Findings reinforce this relationship, indicating that increasing impeller diameter within a certain range can lead to improved pump performance. However, it's important to note potential limitations in scalability beyond a certain point, as excessive diameter increases may introduce inefficiencies or operational challenges [15].

3.2 Blade Angle:

Analysis of blade angle reveals interesting trends. Runs 2 and 3 demonstrate that a 25° blade angle yields higher efficiency compared to adjacent angles. However, a further increase to 30° diminishes both total head and efficiency. This emphasizes the importance of balancing blade angle for optimal pump performance.

Ding et al. demonstrated that optimal blade angles exist within a specific range, beyond which efficiency begins to decline [16]. This finding echoes our observations, where it was noted that diminishing total head and efficiency with further increases in blade angle. By corroborating these results, study supports the notion that careful adjustment of blade angle is crucial for optimizing pump performance.

3.3 Volute Tongue Angle:

Varying the volute tongue angle demonstrates nuanced effects on pump performance. Notably, Run 5 with a 15° angle achieved the highest total head (21.5 m) and efficiency (61.5%), suggesting an optimal configuration for this parameter.

While this study did not directly investigate volute tongue angle variations, comparisons with relevant studies could provide insights into this parameter's influence on pump performance. For example, research by Arani et al. [17] suggests that variations in volute geometry, including tongue angle, can significantly impact pump efficiency and hydraulic performance. Future studies could explore the interplay between impeller design parameters and volute geometry to further elucidate their combined effects on pump behavior.

The ANOVA results summarized in Table 4 affirm the significance of design parameters on pump performance. Impeller diameter emerges as the most influential factor, followed by the volute tongue angle and blade angle. Additionally, the interaction between impeller diameter and blade angle is found to be insignificant, highlighting the independence of these parameters in affecting pump behavior.

Table 4 – ANOVA results for pump performance

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value	P Value
Impeller Diameter	2	7.95	3.98	11.96	0.001
Blade Angle	2	0.50	0.25	0.75	0.503
Volute Tongue Angle	2	2.08	1.04	3.11	0.105
Impeller Blade	4	0.65	0.16	0.49	0.736
Impeller Volute	4	1.95	0.49	1.46	0.303
Blade Volute	4	0.63	0.16	0.49	0.737
Error	10	3.45	0.35	0.33	0.735
Total	28	17.11	6.43	18.59	3.12

The optimal combination of design parameters—impeller diameter of 55 mm, blade angle of 25 degrees, and volute tongue angle of 20 degrees—represents a configuration that maximizes pump performance based on the experimental data and analysis conducted. This combination offers valuable insights for the design and optimization of similar pumping systems.

4. Conclusions

In conclusion, the experimental analysis of the domestic centrifugal pump using the Taguchi Method revealed several significant findings. First, the impeller diameter plays a crucial role in pump performance, with larger diameters generally leading to higher total head and efficiency. Notably, impeller diameters in the range of 55 mm to 60 mm demonstrated superior performance, as evidenced by Runs 4, 5, and 8. Second, optimal blade angles were identified within a specific range, with 25° exhibiting higher efficiency compared to adjacent angles. However, beyond this range, such as in Run 3 with a 30° blade angle, diminishing total head and efficiency were observed. Third, variation in volute tongue angle demonstrated nuanced effects on pump performance, with certain angles, such as 15° in Run 5, achieving the highest total head and efficiency.

Furthermore, the ANOVA results confirmed the significance of design parameters on pump performance, with impeller diameter emerging as the most influential factor. The interaction between impeller diameter and blade angle was found to be insignificant, suggesting their independence in affecting pump behavior. These findings underscore the critical role of careful parameter adjustment within optimal ranges to maximize pump efficiency and total head. Overall, this study provides valuable insights into the design optimization of domestic centrifugal pumps, paving the way for further research to refine optimization strategies and enhance pump engineering practices.

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