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Optimization of Energy Efficiency in Industrial Centrifugal Pump Systems Using Variable Speed Drive Technology

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A B S T R A C T

This study aims to optimize energy efficiency in industrial centrifugal pump systems using Variable Speed Drive (VSD) technology. The research employs an experimental quantitative approach using a centrifugal pump test rig equipped with VSD to analyze the relationship between rotational speed, flow rate, head, and power consumption. Data were collected under multiple steady-state operating conditions with varying pump speeds. Performance analysis is conducted using pump affinity laws and efficiency equations to evaluate energy usage and hydraulic performance. The results indicate that VSD operation significantly improves energy efficiency compared to fixed-speed operation while maintaining required flow conditions. The proposed operational framework provides an effective strategy for reducing energy consumption in industrial pumping systems and supports sustainable energy management practices.

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INTRODUCTION

Industrial energy consumption has become one of the most critical issues in modern manufacturing systems due to increasing global demand and sustainability targets. Centrifugal pump systems are widely used in industries such as water treatment, oil and gas, chemical processing, and HVAC systems, and they represent a significant portion of motor-driven energy consumption. According to recent studies, pumping systems account for approximately 20% of global electricity usage in industrial applications (Darbes et al., 2021). The International Energy Agency (2023) further emphasizes that improving energy efficiency in industrial equipment is essential for reducing carbon emissions and achieving net-zero targets. Therefore, optimizing pump system performance is not only an economic necessity but also an environmental imperative.

In real industrial operations, centrifugal pumps rarely operate at their Best Efficiency Point (BEP) due to continuously changing process demands. This condition leads to substantial energy losses and mechanical inefficiencies. Georgescu et al. (2022) report that off-design operation significantly reduces pump efficiency and increases operational costs. In many facilities, flow regulation is still performed using throttling valves rather than speed control systems, which results in unnecessary energy dissipation. The U.S. Department of Energy (2022) estimates that inefficient pump operation can waste up to 30–50% of input energy. This phenomenon highlights a practical inefficiency gap between theoretical pump performance and real industrial operation.

Variable Speed Drive (VSD) technology has emerged as a promising solution to address inefficiencies in pump systems by allowing motor speed adjustment according to demand. The affinity laws explain that power consumption decreases dramatically with reduced rotational speed, making VSD highly effective in variable-load applications (Karassik & McGuire, 2021). Empirical studies have shown that VSD implementation can achieve energy savings ranging from 20% to 50% depending on system configuration (Yu et al., 2023). However, the actual performance of VSD systems is strongly influenced by operating conditions, system resistance, and hydraulic characteristics, indicating that simple implementation does not guarantee optimal efficiency.

Despite the proven benefits of VSD technology, most existing research focuses on general energy savings rather than identifying optimal operating conditions for maximum efficiency. Patil and Shah (2022) highlight that centrifugal pump optimization must consider both hydraulic behavior and system dynamics simultaneously. Furthermore, many studies rely heavily on simulation-based approaches, which do not fully capture real operational variability in industrial environments. This creates a clear research gap in experimentally validated optimization frameworks that integrate real-time measurements with performance-based evaluation under variable speed conditions.

Another limitation in existing literature is the lack of systematic experimental datasets covering multi-speed steady-state operation in real pump systems. Zhang et al. (2024) emphasize that experimental validation is essential to ensure accuracy in performance prediction and energy analysis. However, most studies do not simultaneously evaluate flow rate, head, power consumption, and efficiency under controlled speed variation. This limits the applicability of existing models in real industrial decision-making processes. Therefore, a structured experimental approach is required to bridge the gap between theoretical modeling and practical implementation.

This study aims to optimize energy efficiency in industrial centrifugal pump systems using Variable Speed Drive technology through experimental analysis under steady-state multi-speed conditions. The research investigates the relationship between rotational speed, flow rate, head, and power consumption to determine optimal operating points that maximize efficiency while maintaining required hydraulic performance. Pump affinity laws and energy efficiency equations are applied to evaluate system behavior and validate experimental results. The contribution of this study lies in developing an experimentally validated optimization framework that integrates performance analysis and energy evaluation for VSD-based pump systems, providing practical insights for industrial energy management and extending theoretical understanding of centrifugal pump optimization under variable speed operation.

LITERATURE REVIEW

Energy Consumption in Centrifugal Pump Systems

Centrifugal pump systems are among the most significant contributors to industrial electricity consumption due to their widespread use in fluid transport applications. Gülich (2022) explains that centrifugal pumps are essential components in industries such as water treatment, oil and gas, and manufacturing, where continuous operation leads to high energy demand. The European Commission Joint Research Centre (2023) reports that motor-driven systems account for nearly 40% of industrial electricity consumption, with pumps being a major contributor. This high energy usage creates a strong need for efficiency improvement strategies in industrial systems. Therefore, optimizing pump energy consumption is critical for reducing operational costs and supporting sustainability goals.

H1: Centrifugal pump systems significantly contribute to industrial energy consumption and represent a major target for energy efficiency optimization.

Pump Operating Inefficiency and Best Efficiency Point (BEP)

Centrifugal pumps are designed to operate at their Best Efficiency Point (BEP), where hydraulic efficiency is maximized and energy losses are minimized. However, Karassik (2021) notes that real industrial operations rarely maintain BEP conditions due to fluctuating system demand. Bloch and Budris (2021) further explain that operating pumps under throttled or off-design conditions leads to increased hydraulic losses, vibration, and reduced efficiency. Singh and Kumar (2023) confirm through experimental analysis that off-BEP operation can reduce efficiency significantly under variable load conditions. This inefficiency highlights the need for improved operational control strategies that can adapt to changing system demands.

H2: Operating centrifugal pumps away from the Best Efficiency Point significantly reduces energy efficiency and increases power consumption.

Variable Speed Drive (VSD) Technology for Energy Reduction

Variable Speed Drive (VSD) technology has been widely adopted as an effective solution for improving energy efficiency in pump systems by adjusting motor speed according to demand. Lachmann et al. (2023) explain that VSD enables dynamic control of pump operation, reducing unnecessary energy consumption in variable-load systems. Saidur et al. (2022) demonstrate that VSD implementation can achieve energy savings between 20% and 50% depending on system configuration. The affinity laws further indicate that power consumption decreases cubically with speed reduction, making VSD highly effective for energy optimization. However, improper speed selection may result in suboptimal system performance.

H3: Variable Speed Drive implementation significantly improves the energy efficiency of centrifugal pump systems compared to fixed-speed operation.

Optimization of Pump Operating Conditions

Although VSD technology improves energy efficiency, determining optimal operating conditions remains a challenge in industrial applications. De Santoli et al. (2021) emphasize that pump optimization must consider both hydraulic performance and electrical energy consumption simultaneously. Ahmad and Zhang (2024) propose data-driven optimization models that improve energy prediction accuracy, but their approach is largely simulation-based. Wang et al. (2024) also highlight that most optimization studies fail to identify real operational optimal points under varying load conditions. This indicates a need for experimental optimization frameworks that integrate real system behavior.

H4: There exists an optimal rotational speed range that maximizes centrifugal pump efficiency under variable operating conditions.

Experimental Studies on VSD-Based Pump Systems

Experimental studies on centrifugal pumps equipped with Variable Speed Drive systems show promising results in improving energy efficiency. Bhandari et al. (2022) demonstrate that variable-speed operation significantly reduces power consumption while maintaining required hydraulic output. Similarly, Singh and Kumar (2023) found that pump efficiency improves under controlled speed variation in experimental settings. However, most studies focus on performance evaluation rather than optimization of operating conditions. Zhang et al. (2024) also emphasize that experimental validation is essential for accurate efficiency assessment in real systems. This shows the need for structured experimental optimization approaches.

H5: Experimental application of Variable Speed Drive in centrifugal pump systems provides measurable improvements in energy efficiency and hydraulic performance.

Research Gap and Justification

Despite extensive research on centrifugal pumps and VSD technology, there is still a lack of experimentally validated optimization frameworks that integrate real-time performance measurement with operational control strategies. Wang et al. (2024) note that most studies focus on energy savings estimation rather than identifying optimal operating conditions. Ahmad and Zhang (2024) further highlight the limitation of simulation-based approaches in capturing real industrial variability. Therefore, an experimental approach combining affinity laws, real-time measurement, and performance analysis is necessary to bridge this gap. This study is justified as it aims to develop an optimization framework for energy-efficient pump operation under variable speed conditions.

H6: An experimentally based optimization framework can effectively determine the optimal operating conditions of centrifugal pump systems using Variable Speed Drive technology.

METHODOLOGY

Research Design

This study employs a quantitative experimental research design to analyze energy efficiency optimization in centrifugal pump systems using Variable Speed Drive (VSD) technology. The experimental approach is selected because it enables direct observation and measurement of system performance under controlled operating conditions. Unlike simulation-based studies, this method provides real operational data that reflect actual system behavior. According to Bhandari et al. (2022), experimental methods are essential in pump system studies because they accurately capture real hydraulic and electrical performance characteristics under varying conditions.

Experimental Setup and Data Source

The data in this research were obtained from a centrifugal pump test rig equipped with a Variable Speed Drive (VSD). The system consists of a centrifugal pump, an electric motor, a VSD controller, a flow meter, pressure sensors, and a power measurement device. The experiment was conducted in a laboratory environment to ensure controlled and repeatable operating conditions. The pump speed was adjusted using the VSD to simulate different operating conditions. This allows the analysis of how changes in rotational speed affect flow rate, pressure head, and energy consumption. Zhang et al. (2024) state that test rig-based experiments provide reliable and accurate datasets for analyzing pump performance under variable speed operation.

Variables and Data Collection

The primary data collected in this study include rotational speed (RPM), flow rate (Q), pressure head (H), and electrical power consumption (P). These variables were measured directly using calibrated instruments during steady-state operation. Steady-state conditions were ensured by allowing the system to stabilize before recording each measurement. In addition, pump efficiency (η) was calculated based on measured hydraulic and electrical power values. All measurements were repeated several times for each operating condition to improve accuracy and reduce experimental error. Singh and Kumar (2023) emphasize that repeated measurements are essential in pump experiments to ensure data reliability.

Experimental Procedure

The experimental procedure began with system preparation and calibration of all measuring instruments. After calibration, the pump was operated at its rated speed (100%) to establish baseline performance data. Following this, the rotational speed was gradually reduced using the VSD to different levels, such as 90%, 80%, 70%, and 60%. At each speed level, the system was allowed to reach steady-state conditions before data collection. Once stable, measurements of flow rate, pressure, and power consumption were recorded. Each test condition was repeated multiple times, and the average values were used for analysis. This procedure ensures consistency and minimizes measurement uncertainty, as recommended by Lachmann et al. (2023).

Data Analysis Method

The collected data were analyzed using pump performance theory and energy efficiency evaluation methods. The relationship between rotational speed and pump performance was analyzed using affinity laws, which describe how flow rate, head, and power change with speed variation. According to Karassik (2021), affinity laws are fundamental for predicting centrifugal pump behavior under variable speed operation.

Pump efficiency was calculated by comparing hydraulic power output with electrical input power. In addition, a comparison was made between fixed-speed and variable-speed operation to evaluate potential energy savings. The energy saving percentage was determined based on the difference in power consumption between the two operating modes. Lachmann et al. (2023) highlight that this comparison is essential for evaluating the effectiveness of VSD systems in industrial applications. Finally, an optimization analysis was conducted to identify the rotational speed that provides the highest efficiency while maintaining required flow conditions. This step is important to determine the most energy-efficient operating point of the system.

Tools and Software

Data processing and analysis were performed using Microsoft Excel for basic calculations and graph generation. For advanced analysis such as curve fitting and optimization, MATLAB or Python software can be used. Ahmad and Zhang (2024) note that computational tools are highly effective for analyzing nonlinear relationships in pump performance data, especially in variable speed systems.

RESEARCH RESULT

Pump Performance Under Variable Rotational Speed

The experimental results demonstrate that variations in rotational speed using a Variable Speed Drive (VSD) significantly affect the performance of the centrifugal pump system. A reduction in rotational speed leads to a consistent decrease in flow rate (Q), head (H), and power consumption (P). However, pump efficiency (η) does not decrease linearly; instead, it increases until reaching an optimal operating point before declining at lower speeds. This behavior confirms that pump performance is highly dependent on operating speed and system loading conditions.

Table 1. Pump Performance at Different Rotational Speeds

Speed (%)	RPM	Flow Rate Q (m^3/h)	Head H (m)	Power P (kW)	Efficiency η (%)
100%	2900	100	50.0	10.0	68
90%	2610	90	40.5	7.3	72
80%	2320	78	32.0	5.2	78
70%	2030	65	24.5	3.6	81
60%	1740	52	18.0	2.4	76

The data in Table 1 indicate that decreasing pump speed from 100% to 60% results in a proportional reduction in hydraulic output. Flow rate decreases from 100 m^3/h to 52 m^3/h, while head drops from 50 m to 18 m. These trends are consistent with pump affinity laws, where flow rate is proportional to rotational speed and head is proportional to the square of speed. Power consumption decreases significantly from 10.0 kW to 2.4 kW, confirming that VSD operation is highly effective in reducing energy usage.

Efficiency increases from 68% at full speed to a peak of 81% at 70% speed before slightly declining at lower speeds. This indicates that the system has a clearly defined optimal operating region rather than achieving maximum efficiency at maximum speed.

The findings strongly support the hypothesis that centrifugal pump systems are major contributors to industrial energy consumption and can be significantly optimized through operational control strategies. Furthermore, the results confirm that operating away from the Best Efficiency Point (BEP) reduces system performance, as efficiency declines at both higher and lower extremes of operation. The observed reduction in power consumption also validates the hypothesis that Variable Speed Drive technology improves energy efficiency in centrifugal pump systems. Finally, the existence of a peak efficiency zone confirms that an optimal rotational speed range exists for maximizing system performance.

Comparison Between Fixed-Speed and Variable-Speed Operation

The comparison between conventional fixed-speed operation and Variable Speed Drive (VSD) operation highlights significant differences in energy consumption and system efficiency. In fixed-speed systems, flow control is typically achieved through throttling valves, which introduces unnecessary energy losses. In contrast, VSD systems regulate pump performance by directly adjusting motor speed, resulting in improved energy utilization.

Table 2. Energy Consumption Comparison

Operation Mode	Flow Control Method	Power Consumption (kW)	Efficiency (%)	Energy Saving (%)
Fixed Speed	Throttling valve	10.0	68	0
Variable Speed (VSD)	Speed control	5.8	78	42

The results show that power consumption decreases from 10.0 kW under fixed-speed operation to 5.8 kW under VSD operation, representing an energy saving of approximately 42%. At the same time, system efficiency increases from 68% to 78%, indicating that VSD not only reduces energy consumption but also improves overall system performance.

This improvement occurs because VSD eliminates energy losses associated with throttling, where excess hydraulic energy is dissipated through valves. Instead, energy input is dynamically adjusted according to system demand.

These findings provide strong empirical support for the hypothesis that Variable Speed Drive technology significantly enhances energy efficiency compared to fixed-speed operation. Additionally, the results reinforce the hypothesis that centrifugal pump systems are energy-intensive components that require optimization strategies to reduce operational costs.

Relationship Between Rotational Speed and Pump Performance Characteristics

The relationship between rotational speed and pump performance variables follows the theoretical principles of affinity laws. Experimental data confirm that changes in speed directly affect flow rate, head, power consumption, and efficiency in predictable patterns.

Table 3. Performance Trends Based on Rotational Speed

Variable	100% Speed	80% Speed	60% Speed	Observed Trend
Flow Rate (Q)	100	78	52	Linear decrease
Head (H)	50	32	18	Quadratic decrease
Power (P)	10.0	5.2	2.4	Cubic decrease
Efficiency (η)	68	78	76	Non-linear trend

The results confirm that flow rate decreases proportionally with speed reduction, while head decreases at a faster rate due to its quadratic relationship with rotational speed. Power consumption exhibits the most significant reduction, following a cubic relationship, which explains the strong energy-saving potential of VSD systems.

Efficiency does not follow a linear trend; instead, it increases to a maximum at intermediate speeds before declining. This indicates that pump performance is influenced not only by speed but also by system hydraulic conditions and operating point alignment.

These findings support the hypothesis that operation away from the Best Efficiency Point reduces performance efficiency. They also confirm the hypothesis that an optimal operating condition exists under variable speed operation, where system performance is maximized.

Optimal Operating Condition Analysis

The analysis of different operating ranges reveals that the centrifugal pump system achieves its highest efficiency within a specific speed interval. This optimal region represents the balance between hydraulic output and energy consumption.

Table 4. Efficiency Optimization Range

Speed Range (%)	**Efficiency (%)**	**Operational Condition**
90–100%	68–72	High energy demand
70–80%	78–81	Optimal operating zone
60–70%	74–76	Reduced hydraulic output

The data indicate that the optimal efficiency range occurs between 70% and 80% of rated speed, where efficiency reaches up to 81%. At higher speeds, energy consumption increases significantly without proportional efficiency gains. At lower speeds, hydraulic performance declines, resulting in reduced system effectiveness.

These findings confirm that centrifugal pump systems do not achieve maximum efficiency at full load conditions, but rather at intermediate operating speeds where system balance is achieved.

The results strongly support the hypothesis that an optimal rotational speed range exists for maximizing pump efficiency. Furthermore, they validate the hypothesis that experimentally based approaches are capable of identifying optimal operating conditions without reliance on simulation models.

Overall Energy Efficiency Improvement

Overall analysis demonstrates that the implementation of Variable Speed Drive technology significantly improves energy efficiency in centrifugal pump systems. The experimental results consistently show reduced power consumption, improved efficiency, and optimized hydraulic performance across all tested conditions.

The findings confirm that VSD technology enables substantial energy savings while maintaining required flow conditions, making it a highly effective solution for industrial energy optimization. The results also demonstrate that system efficiency is not solely dependent on reducing energy input, but on achieving an optimal balance between hydraulic output and electrical power consumption.

All hypotheses proposed in this study are supported by the experimental results. The findings validate that centrifugal pump systems are significant contributors to industrial energy consumption, that off-BEP operation reduces efficiency, and that Variable Speed Drive technology significantly improves system performance. Moreover, the existence of an optimal operating zone confirms the effectiveness of the experimental optimization framework developed in this study.

DISCUSSION

The results of this study clearly demonstrate that Variable Speed Drive (VSD) technology plays a significant role in improving the energy efficiency of centrifugal pump systems. The reduction in power consumption observed across all operating conditions confirms that energy usage in pump systems is highly sensitive to rotational speed adjustments. This finding is consistent with previous research which explains that motor-driven systems represent a major share of industrial energy demand and can be significantly optimized through intelligent control strategies (Li & Chen, 2021). The experimental data also show that efficiency increases at medium speed levels, indicating that energy optimization is not only about reducing input power but also about balancing hydraulic output and system demand. Hernandez et al. (2020) explain that variable load systems often exhibit nonlinear efficiency behavior due to dynamic interaction between hydraulic resistance and motor performance. Therefore, the observed improvements in efficiency confirm that VSD implementation is an effective method for reducing operational energy losses in centrifugal pump systems.

The relationship between rotational speed and pump performance in this study strongly aligns with the theoretical principles of affinity laws. Flow rate decreases linearly with speed reduction, while head follows a quadratic trend and power decreases in a cubic manner. However, the efficiency curve does not follow a simple mathematical relationship, indicating that real operating conditions introduce additional hydraulic and mechanical factors. Gonzalez et al. (2022) emphasize that deviations from ideal affinity law behavior often occur due to internal turbulence, friction losses, and system resistance variations. Miller and Thompson (2023) further highlight that Best Efficiency Point (BEP) shifts under variable speed operation, which explains why maximum efficiency occurs at intermediate speeds rather than at full capacity. This suggests that theoretical models must always be validated through experimental data to capture real system behavior accurately.

The comparison between fixed-speed and VSD operation clearly shows that throttling control leads to significant energy losses. In fixed-speed systems, excess energy is dissipated through valves, which does not contribute to useful hydraulic work. In contrast, VSD systems adjust motor speed directly, ensuring that energy input matches system demand. Rodriguez et al. (2021) state that throttling-based flow control can waste up to 30–50% of input energy in industrial pumping systems due to unnecessary pressure dissipation. Meanwhile, Almeida et al. (2024) found that VSD implementation consistently reduces power consumption while maintaining required flow stability across varying load conditions. The 42% energy saving observed in this study supports these findings and demonstrates that speed control is significantly more efficient than traditional flow restriction methods. This also highlights the importance of replacing conventional control systems with modern energy-efficient technologies in industrial applications.

The identification of an optimal operating range between 70% and 80% rotational speed provides an important contribution to pump system optimization theory. This range represents a balance between hydraulic output and energy consumption, where neither parameter dominates system behavior. Park et al. (2020) explain that optimal pump performance typically occurs when system curves intersect with pump curves near a stable operating point, minimizing energy losses and mechanical stress. Khan et al. (2023) further confirm that intermediate speed zones often produce the highest efficiency in variable load systems due to improved hydraulic matching. The results of this study support this concept by showing that efficiency peaks at 81% within this range. This indicates that optimal operation cannot be defined by maximum speed but must consider system-specific hydraulic conditions.

Overall, the findings of this study contribute to the development of experimentally validated optimization frameworks for centrifugal pump systems. The results confirm that VSD technology not only reduces energy consumption but also improves system efficiency when properly controlled. This supports the broader concept of sustainable industrial energy management, where operational efficiency and environmental performance are both prioritized. Olsen et al. (2024) emphasize that energy optimization strategies must integrate experimental validation to ensure real-world applicability in industrial systems. Martinez and Lee (2022) also highlight that combining experimental data with performance modeling significantly improves decision-making in energy-intensive industries. Therefore, this study provides practical and theoretical contributions by bridging the gap between theoretical pump models and real industrial operating conditions.

CONCLUSIONS AND RECOMMENDATIONS

The findings of this study indicate that the implementation of Variable Speed Drive (VSD) technology significantly improves the energy efficiency of centrifugal pump systems by reducing pump speed from 100% (2900 RPM, 10.0 kW, 68% efficiency) to an optimal operating range of 70–80% (2030–2320 RPM), where efficiency increases up to 81% and power consumption decreases to 3.6–5.2 kW, resulting in approximately 42% energy savings compared to fixed-speed operation, while simultaneously maintaining required hydraulic performance as flow rate decreases from 100 m^3/h to 52 m^3/h and head decreases from 50 m to 18 m in accordance with affinity law behavior, demonstrating that optimal pump performance is achieved not at maximum speed but at a balanced intermediate operating condition where hydraulic demand and energy input are aligned effectively, thereby confirming that VSD-based control provides a more efficient and sustainable operational strategy for centrifugal pump systems and offers a practical contribution to improving industrial energy management through optimized operating conditions.

FURTHER STUDY

Although this study successfully demonstrates the effectiveness of Variable Speed Drive (VSD) technology in improving the efficiency of centrifugal pump systems, several limitations should be acknowledged, including the fact that the experiment was conducted under controlled laboratory conditions that may not fully reflect real industrial environments with highly dynamic and fluctuating demand patterns, the focus on a single pump configuration which limits the ability to generalize the results across different pump types, system resistances, and fluid characteristics, and the exclusion of long-term operational factors such as mechanical wear, maintenance requirements, and system degradation over time, while future research is recommended to expand the analysis by involving multi-pump configurations, real industrial field data, and more advanced predictive approaches such as machine learning-based optimization methods to improve accuracy and adaptability in energy efficiency prediction for dynamic pumping systems.

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