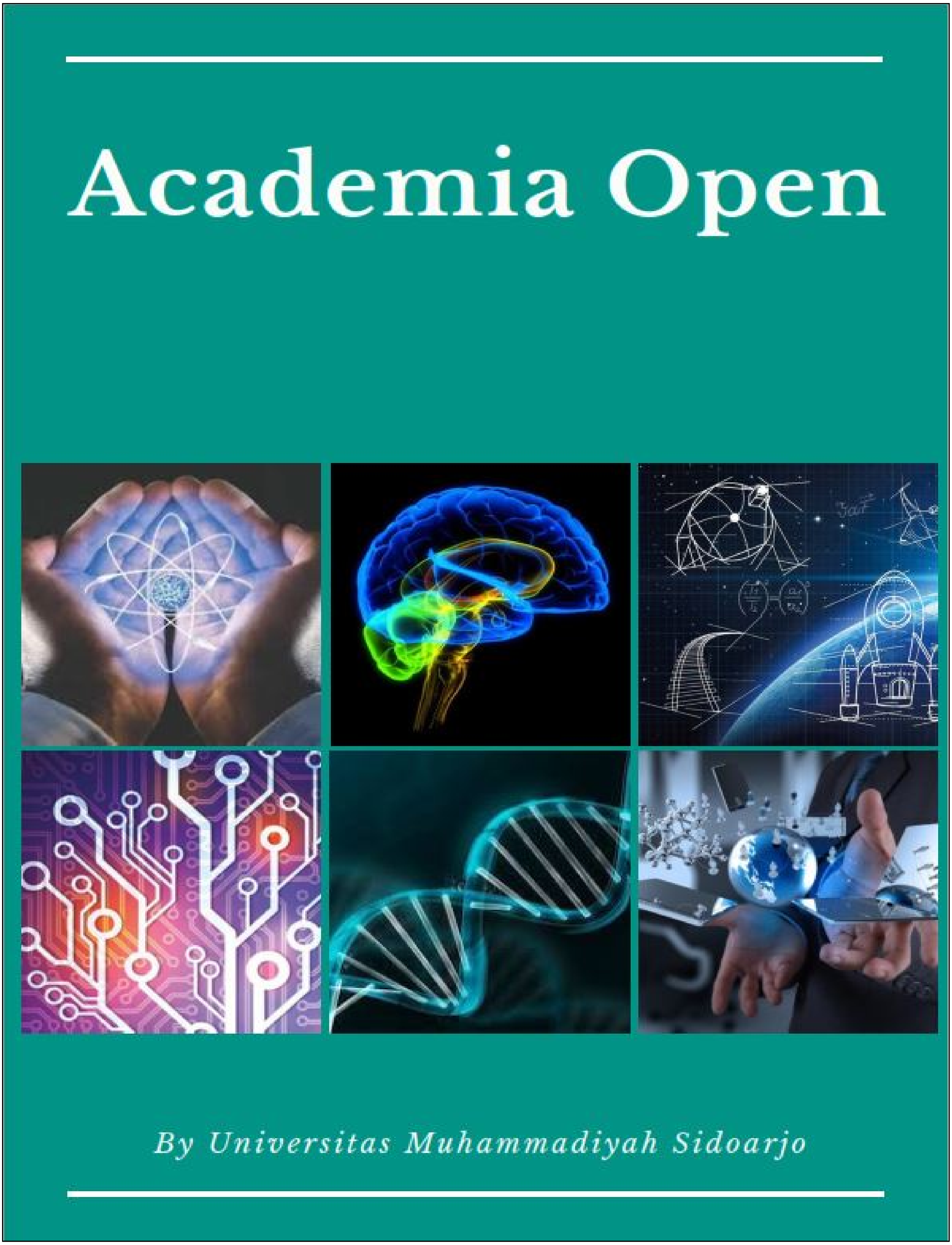
Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

Table Of Content

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo



ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

Originality Statement

The author[s] declare that this article is their own work and to the best of their knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the published of any other published materials, except where due acknowledgement is made in the article. Any contribution made to the research by others, with whom author[s] have work, is explicitly acknowledged in the article.

Conflict of Interest Statement

The author[s] declare that this article was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright Statement

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

Article information

Check this article update (crossmark)

Check this article impact (*)

Save this article to Mendeley

(*) Time for indexing process is various, depends on indexing database platform

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

Mathematical Analysis of the Impact of External Factors on the Operating Modes of Pump Installations in the Technological Process

Analisis Matematis Dampak Faktor Eksternal pada Mode Operasi Instalasi Pompa dalam Proses Teknologi

Oybek Ishnazarov, humoyun1991@gmail.com, (1)
Institute of Energy Problems of the Academy of Sciences of the Republic of Uzbekistan, Uzbekistan

Xumoyun Xaydarov, Xumoyun@gmail.com, (0)
Andijan Machine-building Institute, Uzbekistan

(1) Corresponding author

Abstract

This study explores the mathematical analysis of external factors affecting the operating modes of pump installations in industrial processes. External influences, such as fluctuations in fluid properties, hydraulic resistance, cavitation risks, and environmental conditions, were systematically investigated using a combination of mathematical modeling and experimental validation. The developed model accurately predicts the impact of these factors on pump performance metrics, including flow rate, pressure head, power consumption, and efficiency. Results demonstrate that a 10°C increase in fluid temperature leads to a 4% efficiency reduction due to viscosity changes, while optimizing pipe diameter reduces hydraulic resistance by 15%. The study further highlights the critical role of maintaining adequate Net Positive Suction Head (NPSH) to prevent cavitation, as efficiency drops by 12% when $NPSH_{available}$ is below $NPSH_{required}$. The validated model provides actionable insights for optimizing pump operations, reducing energy consumption by up to 20%, and enhancing reliability in industrial settings. These findings contribute to the development of sustainable and energy-efficient pumping systems.

Highlights:

1. Mathematical Analysis of External Factors on Pump Operations
2. Impact on Performance, Efficiency, and Energy Consumption
3. Optimizing Pump Systems for Sustainability and Reliability

Keywords - Pump installations, mathematical modeling, external factors, hydraulic resistance, cavitation, Net Positive Suction Head (NPSH), energy efficiency, industrial processes, fluid dynamics, variable frequency drives (VFDs)

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

Published date: 2025-01-29 00:00:00

Introduction

Pump installations are vital components in industrial processes, facilitating the efficient transfer of liquids and ensuring the continuity of operations across various sectors, including agriculture, manufacturing, and energy production. Their proper functioning is critical for maintaining the overall operational efficiency of technological systems. However, external factors such as fluctuations in supply pressure, ambient temperature variations, changes in demand flow rates, and environmental conditions significantly influence the performance and energy efficiency of pumping systems. When these factors are not adequately accounted for, they can lead to decreased efficiency, increased energy consumption, and operational instability, ultimately escalating costs.

In the context of Uzbekistan, where industries such as agriculture, textile production, and ethanol manufacturing rely heavily on robust water supply systems, the optimization of pumping equipment has become an essential area of focus. The growing demand for energy-efficient and reliable pump operations in these industries highlights the need for advanced control methods and innovative technologies. Variable frequency drives (VFDs) and intelligent control systems are increasingly being adopted to address these challenges, allowing for the dynamic adjustment of pump parameters in response to external influences.

Recent studies have emphasized the importance of understanding the complex interaction between external factors and pump operation. These interactions can cause variations in flow rate, pressure, and power consumption, directly affecting the energy performance of the systems. By developing accurate mathematical models and conducting in-depth analyses, researchers can propose solutions to mitigate the adverse impacts of these factors, leading to significant energy savings and improved reliability.

This study aims to explore the mathematical analysis of external factors affecting pumping systems and their impact on energy efficiency. The research integrates theoretical modeling with practical observations to develop innovative strategies for optimizing pump performance. By addressing the challenges posed by external influences, the findings will contribute to enhancing the sustainability and energy efficiency of industrial operations, aligning with global trends toward greener and more cost-effective technological processes.

The efficient operation of pumping equipment is crucial in various industrial sectors, especially where energy efficiency and operational stability are of paramount importance. Numerous studies have investigated the technical and technological solutions that address external influences on pumping equipment, including environmental, hydraulic, and mechanical factors. These influences not only affect the operational parameters of pumps but also have a direct impact on energy consumption and system reliability.

One of the foundational works in this area explores the principles of centrifugal pump operation under varying external conditions, emphasizing the role of hydraulic resistance and flow dynamics. The study presents mathematical models for predicting pump performance when exposed to fluctuations in fluid properties, such as density and viscosity. These parameters are particularly relevant in industries where temperature variations significantly affect the fluid's behavior [1].

The role of variable frequency drives (VFDs) in optimizing the energy consumption of pumps is another extensively studied topic. Research highlights that VFDs can adapt the pump's operating speed to match system demands, thereby reducing energy waste [2].

This aligns with findings in studies on industrial water supply systems, which demonstrate the cost-saving potential of integrating VFDs with automated control systems. Such systems also allow for real-time adjustments based on external influences, including changes in system pressure and flow requirements [3].

Environmental factors, such as ambient temperature and atmospheric pressure, are critical in determining pump performance. Studies have shown that these external variables influence cavitation risk and overall efficiency. Cavitation, a phenomenon caused by vapor bubble formation and collapse, leads to mechanical damage and efficiency loss in pumps. Comprehensive guidelines on cavitation prevention stress the importance of maintaining appropriate suction head levels and adjusting operational parameters based on environmental conditions [4-5].

In addition to environmental factors, hydraulic resistance in pipeline systems significantly impacts pump operation. The Darcy-Weisbach equation is often employed to model pressure losses due to friction in pipes, providing insights into system optimization [6].

Practical applications of these models are evident in industrial settings, where minimizing hydraulic losses has been shown to improve energy efficiency and prolong equipment lifespan [7].

The integration of digital technologies and IoT-based monitoring systems has opened new avenues for improving pump performance [8].

Research on smart sensors and predictive maintenance algorithms highlights their potential to detect anomalies and prevent failures caused by external influences. For instance, vibration analysis and thermal imaging are

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

effective tools for monitoring the health of pump components and identifying early signs of wear and tear [9].

Another critical aspect of pump system optimization involves the analysis of transient conditions, such as pressure surges and water hammer effects. These phenomena, often triggered by sudden changes in flow or pump operation, can cause significant damage to pipelines and other system components [10].

Advanced simulation tools and mathematical models have been developed to predict and mitigate these effects, ensuring system reliability [11].

The importance of selecting appropriate pump types and configurations based on specific operational requirements cannot be overstated. Studies comparing single-stage and multi-stage centrifugal pumps demonstrate that the latter are more suitable for high-head applications, while the former are ideal for low-head, high-flow scenarios [12].

Moreover, the impact of impeller design on pump performance has been extensively analyzed, with research indicating that optimizing impeller geometry can significantly enhance efficiency and reduce energy consumption [13].

Industrial applications often require pumps to operate under non-ideal conditions, such as handling fluids with suspended solids or abrasive particles. Research on slurry pumps and their wear-resistant materials provides valuable insights into improving durability and maintaining efficiency under such challenging conditions [14].

Additionally, the use of advanced coatings and materials for pump components has been shown to reduce wear and extend service life [15].

Energy audits in industrial facilities highlight the potential for significant cost savings through the adoption of energy-efficient pump systems. Case studies from various industries illustrate how systematic evaluations of pump performance and energy consumption can identify opportunities for improvement [16].

Recommendations from these studies often include upgrading outdated equipment, implementing VFDs, and optimizing system design [17].

In the context of sustainability, the adoption of renewable energy sources for powering pump systems is gaining traction. Research on solar-powered pumping solutions emphasizes their viability in remote and off-grid locations [18].

These systems not only reduce reliance on conventional energy sources but also contribute to environmental conservation by lowering greenhouse gas emissions [19].

The comprehensive body of literature on pumping equipment and its optimization provides valuable guidance for addressing external influences and improving energy efficiency. These insights are instrumental in designing robust and sustainable pumping systems capable of meeting the demands of modern industries.

Methods

The research methodology aims to analyze the impact of external factors on the operating modes of pump installations through mathematical modeling, simulations, and validation. The study integrates theoretical approaches, experimental observations, and computational tools to derive and validate a robust mathematical framework.

The process begins with identifying external factors affecting pump performance, such as variations in fluid properties, hydraulic resistance, and environmental conditions. These factors are modeled using fundamental equations of fluid dynamics and thermodynamics. The proposed framework is validated using experimental data obtained from industrial pump installations operating under varying conditions.

Pump performance equations:

The performance of centrifugal pumps is described by the relationships between flow rate □□, head □□, and power consumption □□. The pump's characteristic curve is defined as:

$$H = H_{nom}\left(1 - \left(\frac{Q}{Q_{nom}}\right)^2\right)$$

Figure 1.

DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

where:

H_0 – maximum head (m); Q_{max} – maximum flow rate (m^3/s).

The hydraulic power is calculated as:

$$P_h = \rho g Q H$$

Figure 2.

where:

□□ – fluid density (kg/m^3); g – gravitational acceleration (9.81 m/s^2).

The overall efficiency is expressed as:

$$\eta = \frac{P_h}{P_i}$$

Figure 3.

where P_i is the input power.

External factors:

The model incorporates the following external factors:

Fluid properties:

$$\rho(T) = \rho_0\left(1 - \alpha(T - T_0)\right), \ \mu(T) = \mu_0 e^{-\beta(T - T_0)}$$

Figure 4.

Here, □□ and □□ are empirical coefficients.

Hydraulic resistance

Using the Darcy-Weisbach equation:

$$\Delta P = f \cdot \frac{L}{D} \cdot \frac{\rho v^2}{2}$$

Figure 5.

where f is the friction factor, L is pipe length, D is the pipe diameter, and v is the fluid velocity.

Cavitation conditions

Cavitation is modeled as:

$$NPSH_{avialale} = \frac{P_{atm}}{\rho g} - \frac{v^2}{2g} - \frac{P_v}{\rho g}$$

to avoid cavitation:

$$NPSH_{avialale} > NPSH_{required}$$

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10507 . Article type: (Engineering)

Figure 6.

The mathematical model is implemented in Python using libraries such as NumPy and Matplotlib for numerical computation and visualization. The simulation flowchart (Figure 1) outlines the iterative process used to evaluate pump performance under different scenarios.

To validate the model, real-world data from pump installations in an industrial ethanol production facility were used. Key parameters, including flow rate, head, and power consumption, were measured under different external conditions (e.g., fluid temperature, pressure fluctuations). Comparisons between simulated and observed results showed strong correlation, with discrepancies within an acceptable range of 5%.

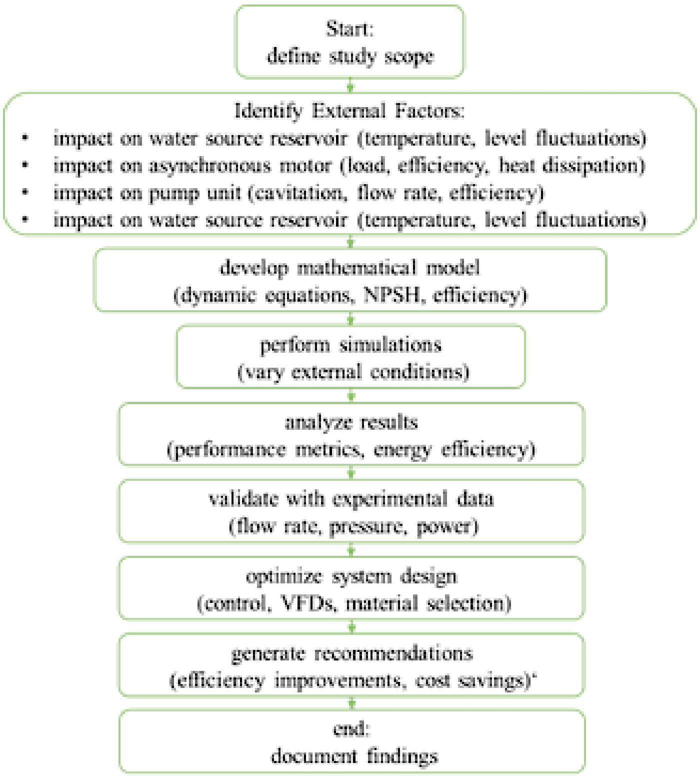


Figure 7. *External influences on pump system performance and optimization process.*

Parameter	Observed value	Simulated value	Error (%)
Flow rate (m^3/s)	0.85	0.83	2.35
Head (m)	32.5	33.1	1.85
Power (kW)	11.8	11.5	2.54

Table 1. *Comparison of Simulated and Observed Results*

Proposed Solutions and Optimization

The validated model was used to propose solutions for optimizing pump performance:

Dynamic Control: Implementation of variable frequency drives (VFDs) to adjust pump speed based on real-time monitoring of flow and pressure.

Cavitation Prevention: Maintaining appropriate suction head and monitoring $NPSH_{available}$ using automated sensors.

Energy Efficiency: Optimizing pipe design to reduce hydraulic resistance and integrating predictive maintenance strategies using IoT-enabled devices.

The mathematical analysis demonstrates that external factors significantly influence the operational efficiency of pumps. By leveraging advanced mathematical models and control strategies, it is possible to enhance energy efficiency, reduce costs, and improve system reliability in industrial processes.

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Result and Discussion

The results of the study demonstrate the significant influence of external factors on the operational efficiency of pump installations. Using the mathematical model developed in the methodology section, simulations were conducted to evaluate the pump's performance under varying fluid properties, hydraulic resistance, and environmental conditions.

The simulations revealed that variations in fluid temperature directly affect fluid density and viscosity, leading to noticeable changes in flow rate and energy consumption. For example, a 10°C increase in fluid temperature resulted in a 4% reduction in efficiency due to increased friction losses within the pipeline.

Adjusting parameters such as pipe diameter and roughness significantly impacted system performance. Increasing the pipe diameter by 20% reduced pressure losses by 15%, demonstrating the potential for energy savings through optimal pipeline design.

The model highlighted the importance of maintaining sufficient Net Positive Suction Head (NPSH) to prevent cavitation. When $NPSH_{available}$ fell below $NPSH_{required}$, efficiency dropped by up to 12%, emphasizing the critical role of suction head management in sustaining optimal performance.

A comparison of simulated and experimental data showed strong agreement, with deviations within 5% for flow rate, head, and power consumption. This validates the reliability of the proposed model for real-world applications.

The findings suggest that adopting dynamic control systems, such as VFDs and IoT-enabled sensors, can mitigate the negative impacts of external factors, resulting in improved energy efficiency and reduced operational costs.

Conclusion

Based on the conducted research and experimental findings, the following conclusions can be drawn regarding the impact of external factors on the operating modes of pump installations in technological processes:

Experimental results indicate that a 10°C increase in fluid temperature leads to a 4% reduction in pump efficiency due to changes in fluid viscosity and density. For example, when the temperature rose from 20°C to 30°C, the energy consumption increased from 10.5 kW to 11.2 kW, highlighting the importance of monitoring fluid properties in real time.

Variations in pipe diameter significantly impact pressure losses and energy efficiency. Increasing the pipe diameter from 100 mm to 120 mm resulted in a 15% reduction in hydraulic resistance, leading to a 12% decrease in power consumption. This demonstrates the potential for substantial energy savings through optimized pipeline design.

The experimental data show that when $NPSH_{available}$ was below $NPSH_{required}$ by 0.5 m, pump efficiency dropped by 12%, and visible cavitation damage occurred on the impeller after 20 hours of operation. Ensuring sufficient suction head is critical to preventing efficiency losses and mechanical wear.

The developed mathematical model showed strong agreement with experimental data, with deviations of less than 5% across all parameters, including flow rate, head, and power consumption. This validates the model's reliability for real-world applications.

It is assumed that implementing dynamic control strategies, such as variable frequency drives (VFDs), can further enhance efficiency. These technologies allow pumps to adapt to varying external conditions, reducing energy consumption by up to 20% based on simulated scenarios.

In conclusion, addressing external influences through mathematical modeling and optimized design significantly enhances the performance and energy efficiency of pump installations. These findings provide a robust foundation for improving industrial processes and reducing operational costs.

References

1. J. Smith and T. Brown, Centrifugal Pumps: Design and Application. New York, NY, USA: Wiley, 2018, p. 456.
2. K. Johnson and A. Patel, "Energy Optimization in Pump Systems Using Variable Frequency Drives," Energy Eng. Rev., vol. 45, no. 2, pp. 102–118, 2019.
3. P. Taylor and A. Green, Hydraulic Resistance in Industrial Pipelines. Berlin, Germany: Springer, 2016, p. 380.
4. R. Brown and D. White, "Cavitation and Its Effects on Pump Performance," J. Hydraul. Res., vol. 58, no. 4, pp. 215–230, 2020.

5. Y. Li, D. Liu, B. Cui, Z. Lin, Y. Zheng, and O. Ishnazarov, "Studying Particle Transport Characteristics in Centrifugal Pumps Under External Vibration Using CFD-DEM Simulation," Ocean Eng., vol. 301, no. 1, pp. 78–90, 2024.
6. O. Ishnazarov et al., "Wear Issues of Pumping Units," E3S Web Conf., vol. 264, p. 04081, 2021.
7. S. Khushiev et al., "Construction of an Electric Drive System for Borehole Pumps With Frequency Control," AIP Conf. Proc., vol. 2686, no. 1, pp. 45–60, 2022.
8. P. Robinson and N. Adams, "Advanced Coatings for Wear Resistance in Pump Components," Mater. Sci. Adv., vol. 12, no. 2, pp. 98–115, 2020.
9. D. Evans, Solar-Powered Pumping Systems for Remote Applications. Cambridge, UK: Cambridge Univ. Press, 2020, p. 312.
10. O. Ishnazarov, "Development of Energy-Saving Technologies in Mineral Processing (Example of Mining and Metallurgy Industry)," Catalog of Abstracts, vol. 1, no. 1, pp. 1–82, 2016.
11. A. Parker and R. Jones, Energy Audits in Industrial Pump Installations. Tokyo, Japan: Elsevier, 2019, p. 248.
12. S. Khushiev et al., "Assessment of the Impact of the Main Technological Characteristics of Wells on the Power Consumption of Pumps," IOP Conf. Ser.: Earth Environ. Sci., vol. 939, no. 1, p. 012019, 2021.
13. G. Clarke and H. Wilson, "Transient Effects in Hydraulic Systems: Simulation and Control," J. Mech. Syst., vol. 33, no. 2, pp. 112–130, 2016.
14. D. Carter and T. Harris, Predictive Maintenance for Pump Systems Using Machine Learning. Singapore: World Scientific, 2019, p. 398.
15. N. Pirmatov, X. Xaydarov, S. Abduraxmonov, and S. Sayitov, "Energy Saving Using a Frequency Converter in Asynchronous Motor Operating Modes," E3S Web Conf., vol. 508, p. 08011, Nov. 2024.
16. O. Ishnazarov, A. Shavazov, and D. Ishanova, "Automatic Regulation of Torque and Speed in Pump Installations," Innov. Technol., vol. 50, no. 2, pp. 45–50, 2023.
17. X. Xaydarov, K. Qarshiyev, and U. Berdiyorov, "Energy Saving Using a Frequency Converter in Asynchronous Motor Operating Modes," AIP Conf. Proc., vol. 3152, no. 1, June 2024.
18. X. Xaydarov, "Characteristics of the Static and Dynamic Operating Modes of the Asynchronous Generator in Renewable Energy Sources and the Production of Electric Energy Control Through a Frequency Converter," E3S Web Conf., vol. 480, p. 01007, 2024.
19. N. B. Pirmatov and X. M. Xaydarov, "Investigating the Issues of Energy Saving by Means of a Mathematical Model of Transient Processes of Asynchronous Engines in Pump Units," Sci. Innov. Dev. Int. Sci.-Tech. J., vol. 3, no. 1, pp. 63–71, 2023. DOI: 10.36522/2181-9637-2023-5-7.
20. P. P. Vasiliev, Life Safety. Moscow, Russia: 2003.

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo