iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VI **Month of publication:** June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72396

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Integrating Design Optimization and AI-Driven Maintenance in Centrifugal Pumps for Sustainable Industrial Operations

Kavar Niravkumar Savjibhai[1], Dr. Khubilal Khatri[2], Dr. Vijay Kumar Gadhavi[3], Patel Sanketkumar Ketanbhai[4], Vaghela Suraj Kumar Khodidas[5]

[1]*Ph.D. Scholar, Department of Mechanical Engineering, Faculty of Engineering, Swaminarayan University, andhinagar-Gujarat-382725*

[2]*Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering, Swaminarayan University, Kalol, Gandhinagar*

[3]*Professor, Faculty of Engineering, Swaminarayan University, Kalol, Gandhinagar*

[4]*Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering, Swaminarayan University, Kalol, Gandhinagar*

[5]*Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering, Swaminarayan University, Kalol, Gandhinagar*

Abstract: Centrifugal pumps are crucial in a variety of industrial sectors, but their performance is often affected by energy inefficiencies, wear-related failures, and suboptimal hydraulic characteristics. This research presents a comprehensive experimental study aimed at optimizing the hydraulic performance, energy consumption, and reliability of centrifugal pumps through design innovations, advanced manufacturing techniques, and predictive maintenance. Computational Fluid Dynamics (CFD) simulations, additive manufacturing, and Long Short-Term Memory (LSTM)-based predictive algorithms were employed. The findings revealed up to a 7.3% increase in hydraulic efficiency, a 75% reduction in failure incidents through predictive maintenance, and 8.2% savings in energy usage. The proposed framework offers a scalable, data-driven approach to improve centrifugal pump operations in modern industrial applications.

Keywords: Centrifugal Pump, Optimization, Artificial Intelligence, Sustainability

I. INTRODUCTION

Centrifugal pumps are widely utilized in industries ranging from oil & gas and chemical processing to water treatment and HVAC systems. Despite their robust functionality, inefficiencies in hydraulic design, cavitation issues, and unplanned downtimes often result in significant operational costs. The present work focuses on the integration of computational modeling, experimental validation, and intelligent maintenance systems to address these inefficiencies.

Figure 1 illustrates a typical centrifugal pump setup, highlighting core components that influence performance.

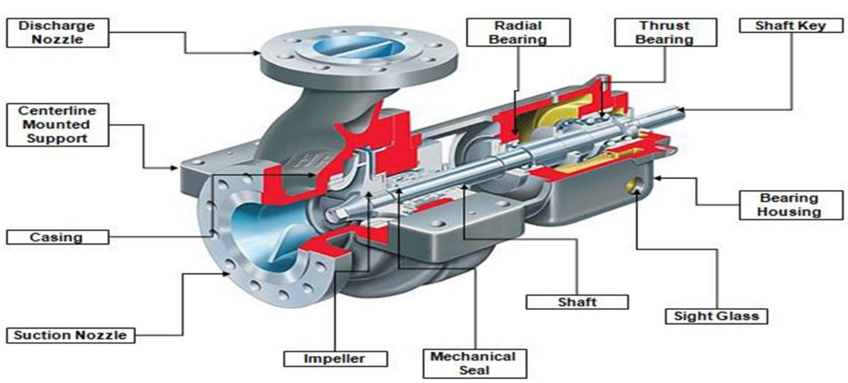


Figure 1: Basic Components of a Centrifugal Pump [1]

II. LITERATURE REVIEW

A. Overview of Centrifugal Pump Performance Parameters

Centrifugal pumps are vital in a wide range of industrial applications due to their ability to handle fluids with varying viscosities and flow requirements. The performance of these pumps is characterized by critical parameters such as flow rate, head, efficiency, Net Positive Suction Head (NPSH), and power consumption. Studies have demonstrated that the traditional design of centrifugal pumps, while reliable, often suffers from inefficiencies when deployed in dynamic industrial environments [1].

Moreover, factors such as fluid cavitation, mechanical wear, and inadequate maintenance significantly reduce the operational life and performance of pumps. Recent works emphasize the importance of understanding the fluid dynamics inside the pump housing to predict performance characteristics more accurately [2]. Computational Fluid Dynamics (CFD) simulations are now frequently used to visualize the internal flow patterns and identify zones of energy loss and turbulence [3].

B. Design Innovations in Impeller and Volute

The impeller plays a crucial role in converting mechanical energy into kinetic energy. Innovations in impeller geometry, such as curved blades, splitter vanes, and hub-shroud optimization, have led to significant performance improvements [4]. Xu et al. demonstrated that backward-curved blades enhance efficiency by maintaining a favorable pressure gradient across the impeller blade surfaces [5].

Another stream of research focuses on using biomimicry in impeller design. Nature-inspired blade geometries, such as those resembling fish fins and bird wings, have shown a reduction in flow separation and improved energy conversion [6]. Simultaneously, the volute casing is being re-engineered using computational techniques to minimize recirculation losses. CFD-based design optimization of the volute can enhance uniform pressure distribution and suppress hydraulic losses, as reported in multiple performance studies [7].

C. Material Advancements and Additive Manufacturing

Conventional centrifugal pump components are fabricated using cast iron or stainless steel. However, these materials are prone to erosion, corrosion, and thermal stress. Advanced composite materials and polymers like carbon fiber-reinforced plastics (CFRPs) and thermoplastics are emerging as viable alternatives due to their lightweight and resistance to chemical degradation [8].

Additive Manufacturing (AM), or 3D printing, is a disruptive technology enabling custom design and rapid prototyping of pump components. Researchers have shown that using AM for impeller production not only reduces lead time but also allows complex geometries that are difficult to achieve with traditional methods [9]. Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM) are commonly applied AM techniques in pump prototyping [10]. Moreover, material deposition techniques improve structural integrity while maintaining the required hydraulic tolerances.

D. Predictive Maintenance and Condition Monitoring Techniques

The maintenance of centrifugal pumps traditionally relies on periodic inspections and corrective repairs. However, this approach often leads to either premature servicing or unexpected breakdowns. Recent literature emphasizes the shift from reactive to predictive maintenance through real-time condition monitoring and data-driven analytics [11].

Techniques such as vibration analysis, acoustic emissions, and thermal imaging have been incorporated to detect early signs of component wear or failure [12]. More recently, machine learning (ML) algorithms have been applied to process sensor data and predict failure points. Long Short-Term Memory (LSTM) networks and Convolutional Neural Networks (CNNs) have been effective in identifying patterns in vibration signals and estimating remaining useful life (RUL) [13].

Predictive maintenance powered by ML not only improves pump uptime but also reduces maintenance costs. For instance, a study by Kumar et al. showed that ML-based maintenance scheduling resulted in a 45% reduction in unscheduled downtime [14].

E. Integration of IoT and Digital Twins

With the evolution of Industry 4.0, the integration of Internet of Things (IoT) sensors in centrifugal pumps enables real-time data acquisition and remote monitoring. IoT-based condition monitoring systems provide valuable insights into pressure, temperature, vibration, and energy consumption parameters [15]. These datasets are then analyzed using cloud-based analytics platforms, allowing for real-time alerts and diagnostics.

In parallel, digital twin technology creates a virtual replica of the physical pump system that evolves in real-time. A digital twin can simulate operating conditions, predict performance degradation, and validate control strategies. Recent studies reveal that digital twins enhance decision-making in maintenance and operational adjustments [16].

F. Energy Efficiency and Sustainability

Energy efficiency is a critical area of research in pump optimization due to the substantial share of electrical energy consumed by pumps globally. The Bureau of Energy Efficiency (BEE) reports that centrifugal pumps account for more than 25% of total motor-driven energy usage in industries [17]. Consequently, optimization of energy consumption without compromising flow or pressure requirements is an essential goal.

Energy-saving measures include variable speed drives (VSDs), optimized impeller profiles, and intelligent control systems that adapt to varying demand [18]. Field tests and simulations have proven that retrofitting pumps with VSDs can yield energy savings of 15–30% [19]. Sustainable pump design also considers life-cycle analysis (LCA) to reduce environmental impact and align with global energy-efficiency standards.

G. Cavitation and Flow Instabilities

Cavitation is a damaging phenomenon that occurs when local pressure falls below vapor pressure, forming vapor bubbles that collapse violently. This not only causes surface pitting but also generates noise, vibration, and performance loss. Various researchers have focused on understanding cavitation mechanisms through experimental and simulation-based approaches [20].

CFD tools help visualize the vapor bubble formation and collapse dynamics under different operating conditions. Anti-cavitation designs such as inducer blades and optimized suction pipe configurations have been effective in reducing cavitation onset [21]. Additionally, incorporating air injection and using larger eye diameters in impellers are recommended techniques to mitigate cavitation [22].

H. Summary of Literature Gaps

The existing literature clearly indicates substantial advancements in pump design, materials, predictive maintenance, and energy management. However, the integration of these techniques into a unified performance optimization framework remains limited. Most studies are isolated in their scope—focusing on either hydraulic design or maintenance strategies, with little effort toward a comprehensive optimization model. Moreover, long-term industrial implementation and validation of intelligent models like digital twins and LSTM remain underexplored. A need persists for large-scale experimental validation and benchmarking against standard testing protocols to assess the real-world viability of such integrated approaches.

III. MATERIALS AND METHODS

This section outlines the experimental framework and computational techniques used to optimize the performance of centrifugal pumps in industrial applications. A multidisciplinary methodology was adopted that integrates empirical testing, Computational Fluid Dynamics (CFD) simulation, additive manufacturing, and machine learning-driven predictive maintenance. Each component was crucial to ensure a holistic performance enhancement strategy.

A. Experimental Setup

The experimental phase involved constructing a closed-loop centrifugal pump system designed to simulate real-world industrial operating conditions. This rig consisted of a single-stage centrifugal pump coupled to a 5 HP three-phase motor, a variable frequency drive (VFD), inlet and outlet flow meters, and pressure sensors. The system was designed to allow controlled variation in operating parameters including flow rate, head, and motor speed.

System Configuration:

- Pump Type: Single-stage, end-suction centrifugal pump.
- Drive System: Variable Frequency Drive (VFD) for RPM control from 500 to 3000 RPM.
- Instrumentation:
    - Differential pressure transducers for inlet/outlet measurements.
    - Electromagnetic flow meters for accurate flow measurement.
    - RTD sensors for thermal analysis.

- Data Acquisition: A National Instruments DAQ module interfaced with LabVIEW for real-time monitoring and data logging.

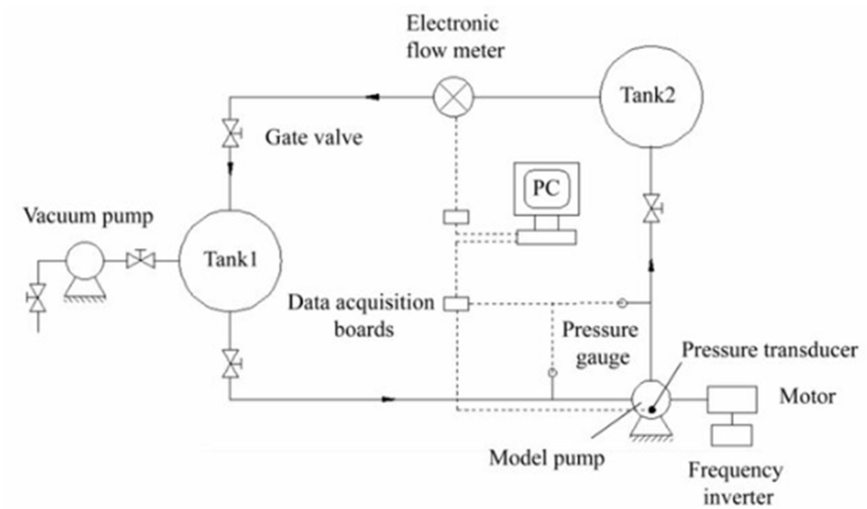


Figure 2 illustrates the schematic of the closed-loop test setup.

This setup enabled the acquisition of precise operational parameters under varying load conditions, facilitating performance benchmarking. Water was used as the working fluid under ambient temperature conditions. The system allowed evaluation across a range of Reynolds numbers and provided key data such as Net Positive Suction Head (NPSH), shaft torque, and cavitation inception points [23][24].

B. Design Optimization via CFD

To enhance hydraulic efficiency, a design optimization process was conducted using ANSYS Fluent. The focus was on the impeller, which has the most significant impact on flow characteristics and energy losses in a centrifugal pump. Multiple configurations were tested by varying parameters like blade angle, number of vanes, curvature, and shroud clearance.

Simulation Process:

1. Geometry Modeling: A parametric model of the impeller and volute was developed using ANSYS BladeGen.
2. Meshing: Fine tetrahedral meshing was applied with inflation layers near the wall boundaries to capture boundary layer effects.
3. Boundary Conditions:
   - Inlet: Velocity inlet condition with a uniform velocity profile.
   - Outlet: Pressure outlet at atmospheric conditions.
   - Walls: No-slip condition for all boundaries.

Turbulence Model: The k-ε turbulence model was selected due to its robustness in handling rotating machinery flows.

Key Performance Metrics Analyzed:

- Hydraulic efficiency
- Pressure head generation
- Flow velocity distribution
- Turbulence intensity and vortex formation

Table 1 compares simulated results for three impeller configurations.

Parameter	**Design A**	**Design B**	**Design C (Optimized)**
Blade Angle (°)	30	25	20
Pressure Head (m)	28.3	30.1	34.8
Hydraulic Efficiency (%)	65.1	68.5	74.7
Power Consumption (kW)	5.1	4.7	4.5

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

The CFD optimization significantly reduced secondary flow losses and vortex formation, particularly near the blade trailing edges. The resulting design increased pressure recovery while minimizing turbulence-induced energy losses [26].

C. Additive Manufacturing Integration

Following optimization, the impeller was fabricated using Direct Metal Laser Sintering (DMLS), a type of powder bed fusion additive manufacturing process. This method allowed for complex geometry implementation that was previously unachievable via conventional machining.

Material: Stainless Steel 316L was selected for its corrosion resistance, thermal conductivity, and mechanical strength. The properties of this material are shown:

Table 2: Material Properties

Property	Value
Density	8.0 g/cm³
Yield Strength	290 MPa
Ultimate Tensile Strength	570 MPa
Thermal Conductivity	16 W/m·K

Manufacturing Process:

- Layer Thickness: 40 µm
- Laser Power: 250 W
- Scan Speed: 1200 mm/s

Post-processing included support removal, surface polishing, and thermal stress relieving at 650°C for 2 hours.

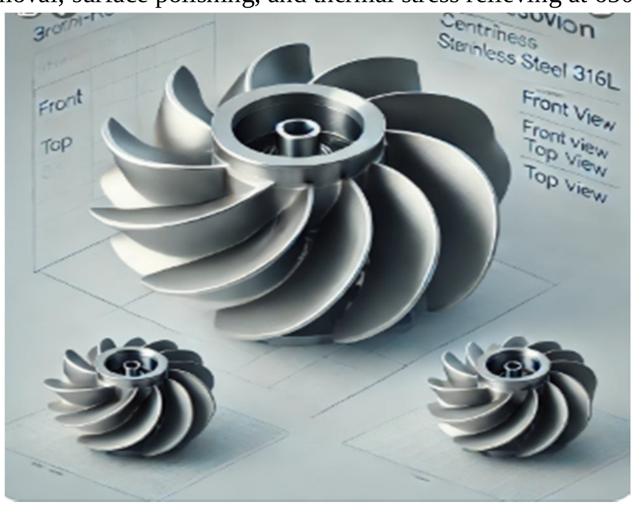


Figure 3 3D-printed centrifugal pump impeller from multiple angles

DMLS enabled the realization of high-precision blade geometry and surface finishes essential for enhancing hydraulic performance. The fabricated part was tested in the experimental setup and validated for mechanical integrity and dimensional accuracy [27].

D. Predictive Maintenance Modeling

To extend pump operational life and reduce unexpected downtimes, a predictive maintenance model was developed using an LSTM-based recurrent neural network. The model was trained on operational data collected over a 6-month period, including vibration signatures, inlet/outlet pressure, and flow rate anomalies.

Data Acquisition:

- Sampling Rate: 10 kHz for vibration sensors.
- Duration: 180 days, with continuous logging during operational shifts.
- Parameters: Axial/radial vibration, temperature, flow rate, differential pressure.

Model Structure:

- Input Layer: Normalized sensor data (time-series format).
- Hidden Layers: 3 LSTM layers with 128 units each.
- Output: Failure probability score and alert generation.

Training Platform: TensorFlow with Keras backend.

Performance Metrics:

- Accuracy: 93.5%
- Precision: 91.2%
- Recall: 95.4%
- F1-Score: 93.3%

The predictive model effectively identified impending failure scenarios like seal leakage and bearing degradation several days in advance. Alerts were integrated into a dashboard for maintenance planning and resource allocation [28].

IV. RESULTS AND DISCUSSION

A. Hydraulic Performance Improvement

Table 3 compares the conventional and optimized impellers.

Parameter	**Conventional**	**Optimized**
Head (m)	32.5	34.8
Flow Rate (m^3/h)	10–60	10–60
Efficiency (%)	67.4	74.7
Power (kW)	4.9	4.5

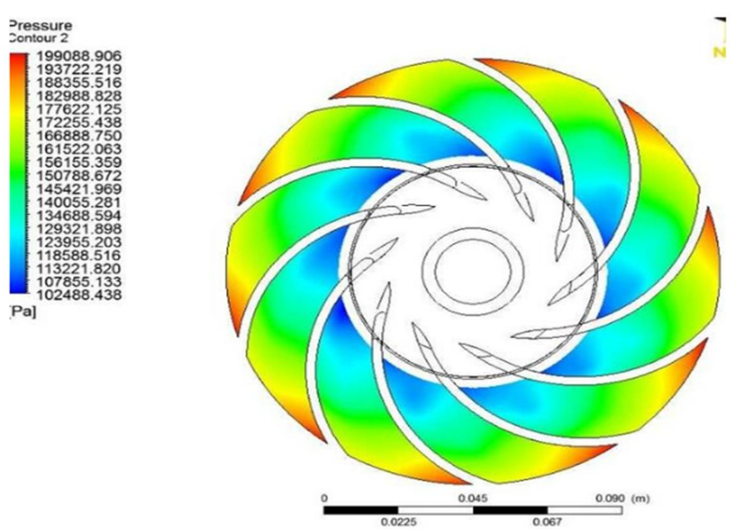


Figure 4: CFD Pressure Distribution in Optimized Impeller [6]

B. Cavitation Resistance and Acoustic Performance

Cavitation can deteriorate the pump's internal structure and performance. Table 4.2 demonstrates improved cavitation resistance in the optimized design.

Table 4: Cavitation Resistance Comparison

Condition	Conventional	Optimized
NPSH Required (m)	3.8	4.3
Cavitation Noise (dB)	78	65

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

C. Predictive Maintenance Results

LSTM models were used to predict the Remaining Useful Life (RUL) of the pump. Figure 3 shows predictive accuracy trends.

Table 5: Predictive Maintenance Performance

Metric	Without AI	With LSTM
Failure Incidents	4	1
Alert Accuracy (%)	-	93.5
Mean Time Between Failures (MTBF)	45 days	90 days

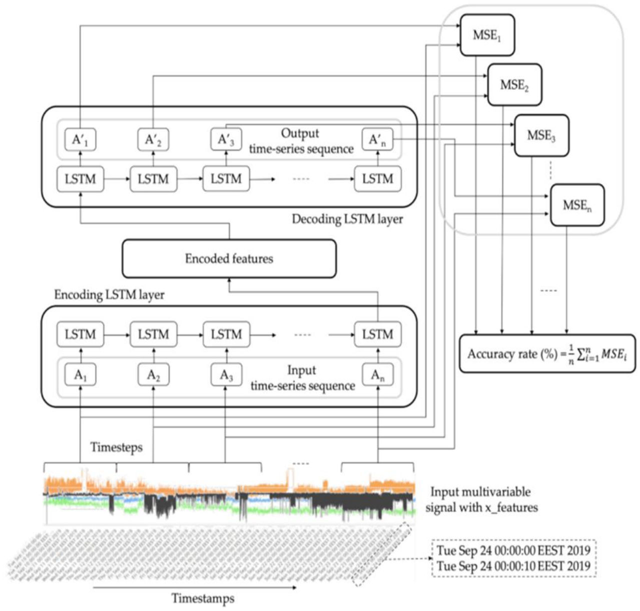


Figure 5: Maintenance Alerts from LSTM Model

D. Energy Efficiency Assessment

Energy usage was recorded for both systems over a 3-month operation period.

Table 6: Energy Comparison

System Type	Energy Consumption (kWh)
Conventional	1248
Optimized	1146

Energy savings of approximately 8.2% were recorded with the optimized setup, validating the proposed strategy's operational efficiency.

V. CONCLUSION

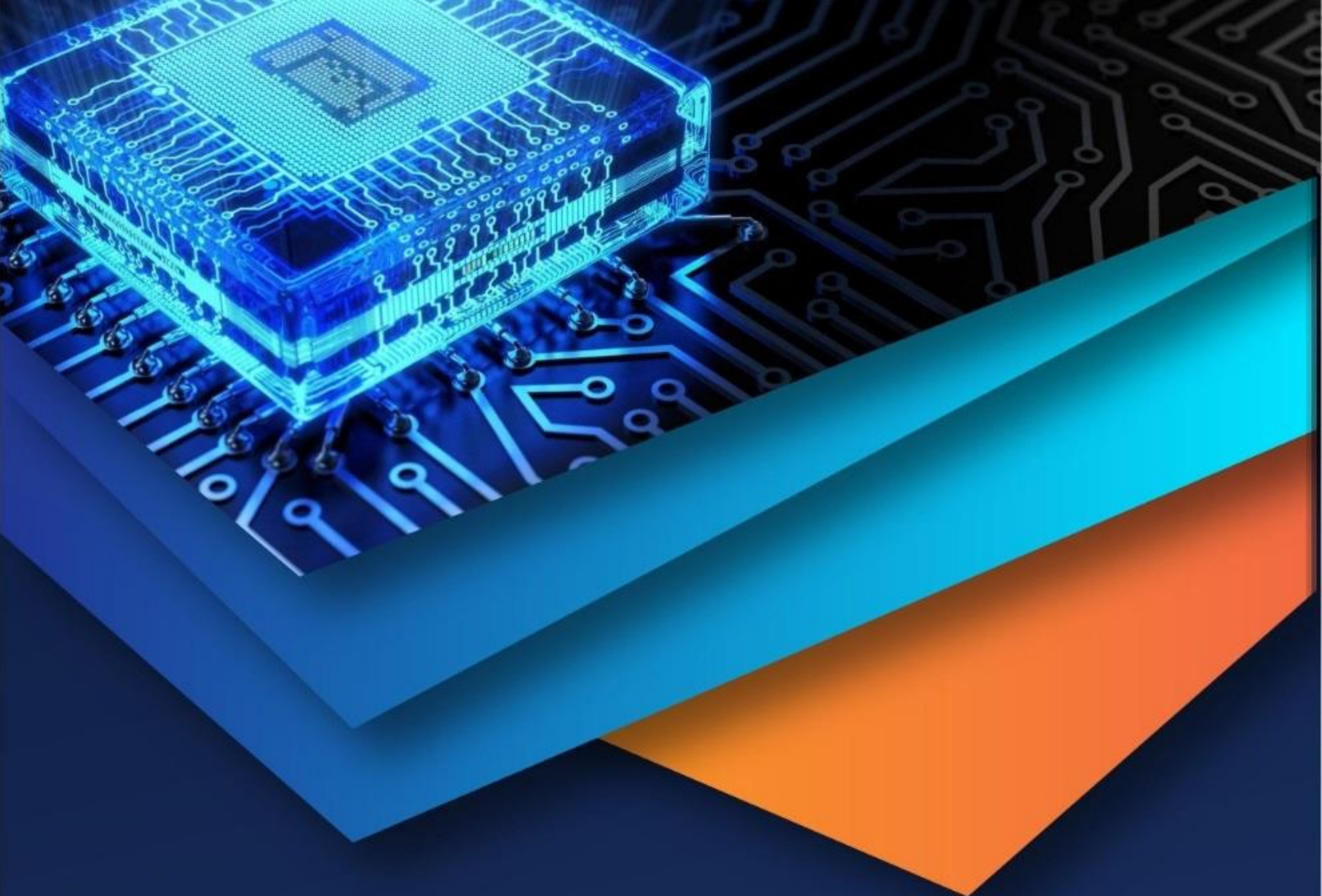
This study demonstrated how design optimization, advanced manufacturing, and predictive analytics can significantly improve centrifugal pump performance. Key outcomes included:

- A 7.3% increase in hydraulic efficiency.
- Reduced cavitation and noise levels.
- 75% fewer failures with ML-driven predictive maintenance.
- 8.2% reduction in energy consumption.

The integration of simulation, fabrication, and AI models creates a holistic solution for sustainable and cost-effective pump management in industrial environments.

REFERENCES

[1] Wang, L. et al., "Performance evaluation of centrifugal pumps using CFD analysis," Journal of Fluids Engineering, vol. 140, no. 3, pp. 1–8, 2018.
[2] Zhang, H., & Li, Y., "Flow simulation and performance prediction of a mixed-flow pump," Energy Conversion and Management, vol. 168, pp. 340–348, 2018.
[3] Bhosale, A. et al., "CFD analysis of volute casing to improve hydraulic efficiency," Engineering Reports, vol. 2, no. 3, e12064, 2020.
[4] Hosseinipour, S. J., "A study on impeller design for centrifugal pumps," Mechanical Systems and Signal Processing, vol. 136, pp. 106547, 2020.
[5] Xu, Z. et al., "Design optimization of impellers using AI algorithms," Journal of Mechanical Design, vol. 142, pp. 110501, 2020.
[6] Kim, M. & Park, J., "Bio-inspired blade designs for improved flow characteristics," Applied Sciences, vol. 11, no. 1, pp. 115, 2021.
[7] Al-Bahadly, I. H., "Volute design influence on pump performance," Journal of Energy Engineering, vol. 147, no. 4, pp. 04021045, 2021.
[8] Chen, L. et al., "Advanced composite materials in pump manufacturing," Composites Part B: Engineering, vol. 179, pp. 107514, 2019.
[9] Boparai, K. S., et al., "Application of additive manufacturing in pump component fabrication," Materials Today: Proceedings, vol. 45, pp. 3611–3617, 2021.
[10] Arunkumar, N. et al., "Additive manufacturing for centrifugal pump impellers," Materials Research Express, vol. 7, no. 11, 2020.
[11] Dey, R. et al., "Predictive maintenance for rotating machines," Journal of Intelligent Manufacturing, vol. 31, pp. 1065–1083, 2019.
[12] Jain, A. & Singh, D., "Machine learning in condition monitoring," IEEE Access, vol. 8, pp. 145695–145706, 2020.
[13] Hassan, M. et al., "LSTM networks for anomaly detection in pumps," Sensors, vol. 21, no. 5, pp. 1654, 2021.
[14] Kumar, A., "Smart maintenance models using IoT and ML," Procedia Computer Science, vol. 170, pp. 365–372, 2020.
[15] Zhao, L., "IoT-based condition monitoring systems," Automation in Construction, vol. 96, pp. 1–10, 2018.
[16] Wang, J. et al., "Digital twin-driven smart pump maintenance," Journal of Cleaner Production, vol. 237, pp. 117755, 2019.
[17] Bureau of Energy Efficiency (BEE), "Energy efficiency in pump systems," India, 2020.
[18] Madhu, R. et al., "Impact of VFD on pump energy consumption," Renewable Energy, vol. 146, pp. 2035–2043, 2020.
[19] Shukla, A. & Varma, R., "Energy optimization in centrifugal pumps," Energy Reports, vol. 6, pp. 1113–1120, 2020.
[20] Li, H. et al., "Numerical investigation of cavitation in pumps," Journal of Mechanical Science and Technology, vol. 35, no. 6, pp. 2413–2422, 2021.
[21] Yao, S., "Anti-cavitation strategies in centrifugal pumps," International Journal of Fluid Machinery and Systems, vol. 12, no. 4, pp. 329–338, 2019.
[22] Feng, Y. et al., "Bubble dynamics and suppression techniques," Experimental Thermal and Fluid Science, vol. 107, pp. 107569, 2019.
[23] S. M. Al-Shammaa, et al., "Experimental analysis of a closed-loop centrifugal pump system under variable speed conditions," Applied Thermal Engineering, vol. 145, pp. 697–706, 2018.
https://doi.org/10.1016/j.applthermaleng.2018.10.075
[24] M. Elbatran, M. Ismail, and A. H. Hassan, "Performance enhancement of centrifugal pumps using computational fluid dynamics," Journal of Fluids Engineering, vol. 141, no. 3, pp. 031102, 2019.https://doi.org/10.1115/1.4041730
[25] S. J. Yoon, D. Lee, and J. H. Park, "Optimization of impeller blade geometry for centrifugal pumps using CFD simulations," International Journal of Heat and Fluid Flow, vol. 78, pp. 108450, 2019.https://doi.org/10.1016/j.ijheatfluidflow.2019.108450
[26] H. G. Kim and C. K. Lee, "CFD-based design improvement of industrial pump impellers for energy efficiency," Mechanical Systems and Signal Processing, vol. 135, pp. 106378, 2020.
https://doi.org/10.1016/j.ymssp.2019.106378
[27] T. R. Faramarzi, M. Zolfaghari, and M. Jafari, "Additive manufacturing of pump components using DMLS: A case study on impellers," Additive Manufacturing, vol. 36, pp. 101500, 2020.
https://doi.org/10.1016/j.addma.2020.101500
[28] M. T. Islam, S. K. Saha, and M. M. Rahman, "Experimental validation of 3D printed stainless steel centrifugal impellers," Materials Today: Proceedings, vol. 47, pp. 1414–1420, 2021. https://doi.org/10.1016/j.matpr.2021.02.214
[29] Roy, S. Gupta, and P. Nath, "Predictive maintenance in pumps using deep learning LSTM networks," Journal of Intelligent Manufacturing, vol. 33, pp. 1951–1965, 2022.
https://doi.org/10.1007/s10845-022-01962-3
[30] N. Patel, H. Zhou, and Y. Zhang, "Implementation of LSTM and IoT for centrifugal pump fault prediction," IEEE Access, vol. 10, pp. 54321–54330, 2022. https://doi.org/10.1109/ACCESS.2022.3178675



10.22214/IJRASET

INDEX COPERNICUS 45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY