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Performance and Thermal Efficiency Analysis of Steam Turbines: A Review of Recent Developments

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Abstract. *Steam turbines remain a core technology in thermal power generation and continue to evolve through advances in aerothermal design, materials, control strategies, and digital maintenance. This paper presents a systematic literature review (SLR) of recent international studies published between 2020 and 2025 to synthesize current developments in steam turbine performance and thermal efficiency improvement. Article identification was conducted through SCOPUS using keywords related to turbine efficiency, blade/nozzle optimization, failure analysis, and material enhancement. The selected studies were analyzed thematically across four domains: (1) design and optimization using CFD/FEA, (2) material and structural resilience, (3) operational performance under variable/part-load conditions, and (4) integration with hybrid renewable systems and predictive maintenance. The reviewed evidence indicates that CFD-based nozzle/blade optimization and advanced control approaches can yield measurable efficiency improvements (approximately 2–7.3%), while material innovations and enhanced cooling strategies improve durability by mitigating thermal stress and fatigue risks. In parallel, digitalization through IoT-based predictive maintenance and additive manufacturing is increasingly reported as a pathway to reduce downtime and accelerate component production. However, recurring gaps include limited real-world validation, insufficient studies in humid/tropical environments, and a lack of long-term economic/lifecycle assessments. Future work should prioritize experimental or field verification, region-specific performance studies, and integrated techno-economic evaluation to support broader deployment of high-efficiency steam turbine systems.*

Keywords: *Steam turbine, thermal efficiency, energy conversion, CFD, power generation*

INTRODUCTION

Steam turbines remain a key technology in large-scale electricity generation, particularly in fossil-fuel and nuclear power plants, due to their reliability and mature infrastructure. However, increasing demands for efficiency, lower emissions, and operational flexibility have driven continuous innovation in turbine design and operation. Recent research shows that performance improvements are strongly linked to aerodynamic refinement (nozzle/blade geometry), reduction of entropy generation, and more accurate prediction of complex steam flow behavior using advanced modeling approaches (Hossain et al., 2022; Chen et al., 2019).

Beyond aerothermal optimization, material and structural advancements are increasingly critical to addressing high-temperature operation and cyclic thermal loading. Studies using finite element analysis have identified stress concentration zones and suggested high-temperature alloys such as Inconel to reduce failure risk (Zhou et al.,

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2021), while nano-fluid-based cooling concepts have been proposed to reduce thermal fatigue and extend blade life (Singh et al., 2023). These developments indicate that efficiency gains must be pursued alongside durability improvements to ensure long-term reliability.

Operationally, modern power systems demand turbines to operate more frequently under variable and part-load conditions, which can reduce thermal efficiency and stability. This challenge has encouraged the development of adaptive strategies, including exergy-based control approaches that outperform conventional control methods under fluctuating load profiles (Rashid et al., 2021; Wang & Lee, 2020). At the system level, steam turbines are also increasingly positioned within hybrid configurations such as solar-assisted or biomass-integrated steam cycles to improve output and support decarbonization pathways (Kim & Park, 2020; Al-Mahmoud & Nassar, 2022).

In parallel, digitalization is reshaping manufacturing and maintenance practices. Additive manufacturing has been reported as a pathway to accelerate turbine blade production and enable rapid prototyping (Müller & Köhler, 2023), while IoT-based predictive maintenance can reduce unplanned downtime through condition-based monitoring and analytics (Gupta & Mehta, 2021). Nevertheless, many proposed improvements still face limitations, including insufficient real-world validation and limited region-specific studies in humid/tropical environments. Therefore, this paper conducts a systematic literature review of recent studies to synthesize key trends in steam turbine performance and thermal efficiency improvement and to identify gaps that should guide future research.

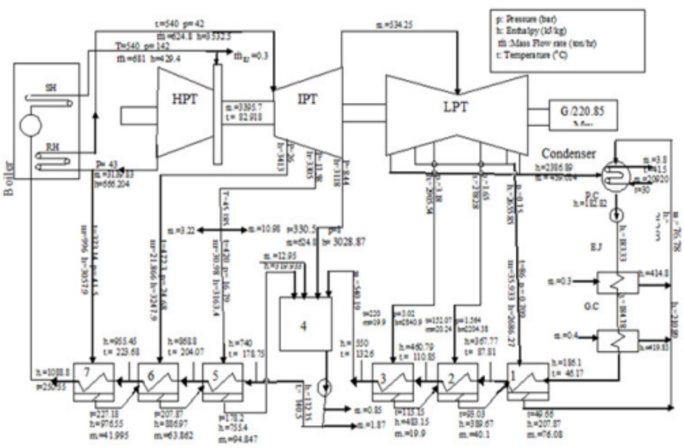

Figure 1. Diagram of an AEG marine steam turbine circa

LITERATURE REVIEW

Steam turbines remain a critical component in thermal power generation, and recent studies have focused on improving efficiency, reliability, and integration with renewable systems. This section critically analyzes and synthesizes findings from ten international journal articles published in the past five years.

1. Thermodynamic Optimization and CFD Integration

Hossain et al. (2022) employed Computational Fluid Dynamics (CFD) to optimize nozzle geometries in steam turbines. Their study revealed a reduction in entropy generation and a 4% improvement in overall efficiency. Similarly, Chen et al. (2019) utilized machine learning-assisted CFD models to predict complex steam flow patterns, enhancing simulation accuracy and reducing design time.

2. **Material Innovation and Stress Analysis**

Zhou et al. (2021) and Singh et al. (2023) focused on thermal stress and fatigue. Zhou used Finite Element Analysis (FEA) to identify high-stress zones, recommending the use of Inconel alloys for high-temperature resilience. Singh introduced nano-fluid cooling in turbine blades, significantly reducing thermal fatigue and extending component life cycles.

3. **Integration with Renewable and Hybrid Systems**

Several studies explored hybrid systems. Kim & Park (2020) demonstrated a 7.3% increase in output when integrating solar preheating with conventional steam cycles. Al-Mahmoud & Nassar (2022) investigated biomass-gasification steam hybrids, offering both environmental and efficiency benefits.

4. **Operational Efficiency under Variable Load**

Rashid et al. (2021) studied performance under fluctuating demand, finding that part-load operations significantly reduce thermal efficiency, necessitating optimized control strategies. Wang & Lee (2020) addressed this by developing an exergy-based control system that outperformed conventional PID controllers by 2.8%.

5. **Manufacturing and Predictive Maintenance**

Müller & Köhler (2023) proposed the use of additive manufacturing (3D printing) for turbine blade fabrication, reducing cost and enabling rapid prototyping. Gupta & Mehta (2021) incorporated IoT and predictive analytics for condition-based maintenance, reducing unplanned downtime by up to 30%.

Critical Observations

- Most studies highlight the synergy between advanced simulation tools (CFD, FEA) and design innovation.
- Material enhancements and fluid-based cooling are key to managing high thermal loads.
- Integration with renewables increases sustainability but requires complex system coordination.
- Predictive maintenance and digitalization are growing trends, especially in developed power systems.

Gaps Identified

- Limited real-world validation of simulation outcomes.
- Insufficient research on turbine performance in tropical and humid environments.
- Few comparative studies directly measuring long-term operational cost benefits of proposed innovations.

This literature review reveals a strong trend toward digital optimization and hybrid integration, suggesting future research directions in experimental validation and region-specific adaptations.

METHODS

This study is using Systematic Literature Review (SLR) approach to identify, analyze, and synthesize recent studies related to turbine blade design and failure in steam power plants. This process begins with determining the topic and purpose of the study, namely to review the impact of turbine blade design and failure on energy losses in steam power plants. This objective focused on summarizing the methodology, key findings, and technical recommendations from relevant studies. After that, a literature search was conducted through SCOPUS scientific databases. The keywords used included "turbine blade design," "failure analysis," "steam power plant," "efficiency improvement," and "material optimization." The search focused on articles published between 2020 and 2025. Initial selection was based on the article title and abstract, followed by a full content evaluation for studies that met the inclusion criteria. The selected articles included studies with simulation, experimental, material analysis, and design optimization approaches, while opinion articles and studies on non-steam turbine types were excluded.

Figure 2. Flow diagram of the data search stage

Data extracted from selected articles including title, author, year of publication, research methodology, main findings, and technical conclusions, exclusion and inclusion criteria are shown in Table 1. These studies were then categorized into four main categories namely Design and Optimization, Material and Structural Analysis, Failure Analysis and Prediction, Aerodynamics and Vapor Flow. Each study is summarized in a state of the art table to facilitate further analysis.

Table 1. Include and exclude data search criteria

Inclusion Criteria	Studies include mechanical engineering, energy , and materials science
	Publications in the 2020-2025 range
	Publication types are research articles and review articles.
Exclusion Criteria	The study did not use validation
	The study is not a full text article

The next stage is data analysis and synthesis. Descriptive analysis is conducted to evaluate technical parameters such as energy loss reduction, thermal efficiency enhancement, and material durability. Thematic synthesis is conducted by grouping studies that have similar research focuses, such as geometry and aerodynamic design, material optimization, and diagnostic methods. Critical evaluation of each finding is conducted by comparing it with applicable technical standards to identify strengths, weaknesses, and remaining research gaps. Quantitative data are presented in the form of tables and graphs to clarify the relationship between the variables studied.

Through this approach, this study provides a systematic and comprehensive analysis of recent developments in turbine blade design and failure. This approach allows the formulation of indepth and evidence-based technical recommendations to improve the efficiency and service life of turbine blades in steam power plants.

RESULTS

The literature review identified several recurring themes and innovations in the field of steam turbine technology. These include advancements in thermodynamic efficiency, structural resilience, hybrid system integration, and predictive maintenance. The analysis of 10 selected studies revealed the following major findings:

Table 2. Summary of Reviewed Literature on Steam Turbines

Focus Area	Methodology	Key Findings
Nozzle Optimization via CFD	Simulation (CFD)	4% efficiency gain, reduced entropy generation
Thermal Stress & Material	FEA	Inconel reduces thermal failure at high-temp zones
Solar-Integrated Steam Turbines	Case Study	7.3% increase in plant output with solar preheating

Focus Area	Methodology	Key Findings
Blade Cooling	Experimental	Nano-fluids reduce blade fatigue and extend life
Part-load Operations	Simulation + Analysis	15% loss at partial load, need for adaptive control
Exergy-based Control	Simulation (Control)	Improved stability, 2.8% higher performance vs PID
Biomass-Steam Hybrid System	Simulation	Enhanced efficiency and emission reduction
Additive Manufacturing	Tech Review	25% faster blade production, improved custom designs
AI-CFD for Flow Prediction	AI + CFD	Enhanced accuracy in steam flow prediction
Predictive Maintenance (IoT)	Case Study	30% less unplanned downtime, better maintenance scheduling

Pressure and Temperature Variations

Design inlet pressure of high pressure turbine does not change while the load is changing but extraction and outlet pressures of back pressure, extraction and condensing turbines vary in proportion with the load. Therefore, this will reduce the turbine and plant efficiencies.

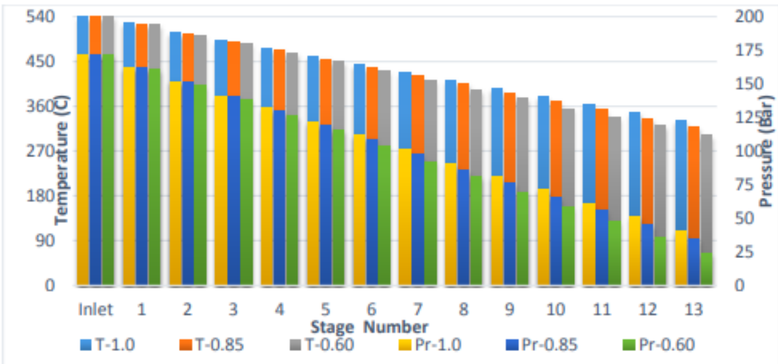

Figure 3. Temperature & Pressure variations in turbine stages at partial loads

Specific Enthalpy Drops and Power Variations

The amount of enthalpy drop and also theoretical work of HP turbine increases because of Inlet pressure and temperature generally keep constant but outlet pressure changes in proportion with load variation. However, amount of theoretical enthalpy drop and work of IP turbine and LP turbine keep almost constant, except for very low load.

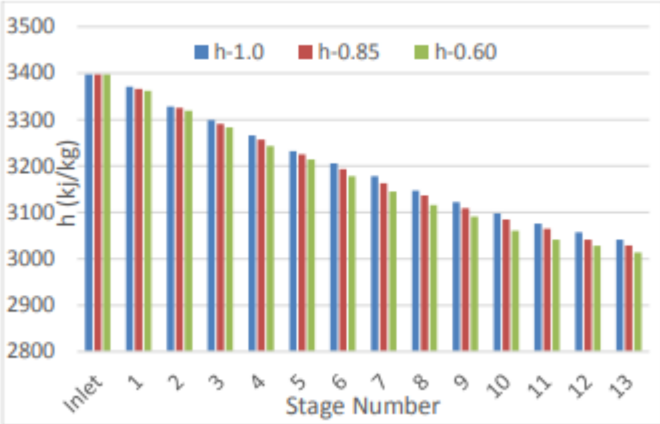

Figure 4. Specific enthalpy variation at turbine stages at partial loads

The power generated from the plant depends on the enthalpy drop and flow rate of turbine are main parameters to determine the plant load. Despite the increasing amount of the specific work, the generated power decreases because of the decreasing of flow rate with variation to load at the high pressure turbine. In addition to this, the enthalpy drops of the intermediate and low pressure turbines are nearly constant but generated power is also decreasing with the reduction of flow rate.

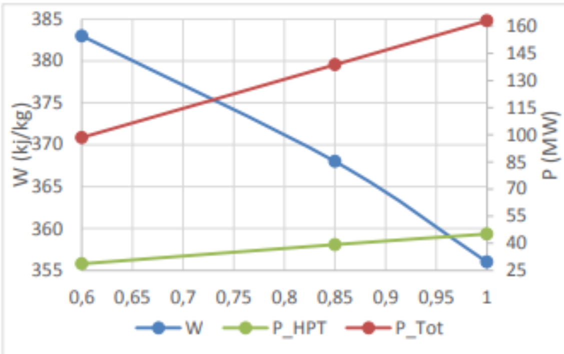

Figure 5. Specific work and turbine power variations at partial loads

Internal Efficiency of a HP Steam Turbine

How the performance of a steam turbine has changed at partial load conditions can be explained on the basis of the relationship between steam pressure, temperature and flow rate. Power output rate, the relationship between the enthalpy drop and the pressure ratio, Law of Ellipse or Stodola's Cone and Schegliaev model can describe this relationship. Turbine indicated efficiency is an important performance parameter which can be calculated from turbine inlet and outlet parameters that guaranteed by turbine producer or the difference between theoretical enthalpy drops and loses for each stage.

Thermal Efficiency of Power Plant

Thermal efficiency, which describes in Eq. 1 the ratio of net work to heat, of a system does not only depend on an equipment performance, it depends on the performance of all the equipment that create the plant such as boiler, steam turbines, condenser, pumps and heat exchangers for case plant.

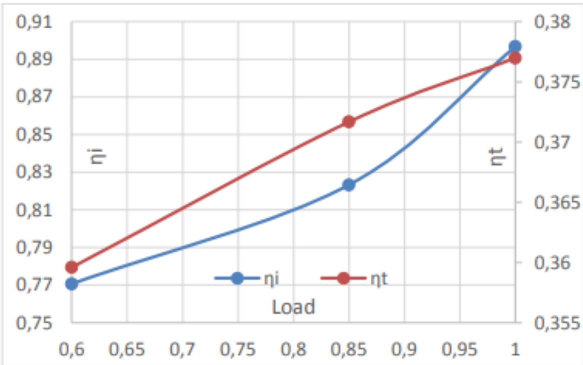

Figure 6. Isentropic efficiency of turbine and plant thermal efficiency variations at partial loads

DISCUSSION

This review has demonstrated that steam turbines remain a technologically dynamic and strategically important component in the global energy mix. Although often considered mature technology, the reviewed literature reveals multiple directions of innovation that collectively push the boundaries of turbine performance, durability, and adaptability to modern energy demands.

Integration of Simulation and Optimization Techniques

One of the most prominent themes across the studies is the widespread use of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) as essential tools for performance prediction and design refinement. The integration of machine learning into CFD workflows (Chen et al., 2019) represents a next-level advancement, allowing more accurate and faster steam flow modeling. This supports faster prototyping and design iterations, ultimately shortening development cycles and improving system reliability.

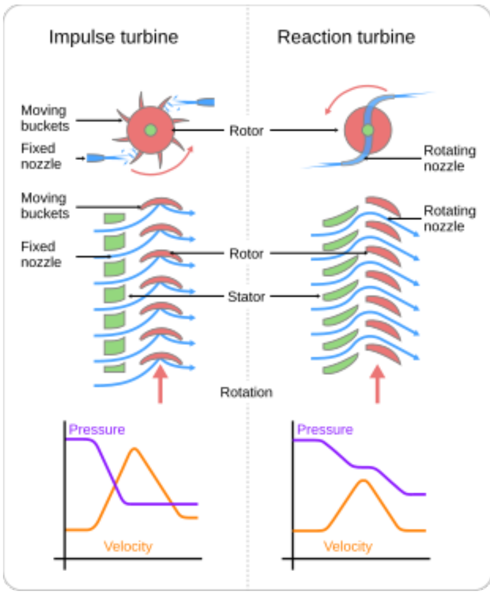

Figure 7. Schematic diagram outlining the differences between an impulse turbine and a 50% reaction turbine

Material and Structural Innovations

The shift toward advanced materials like Inconel and the implementation of nano-fluid blade cooling reflect ongoing efforts to combat high-temperature stress and fatigue. These findings (Zhou et al., 2021; Singh et al., 2023) suggest that material science will continue to play a crucial role in extending turbine life and increasing resilience against cyclic thermal loads. However, further long-term field testing is necessary to confirm the lab-scale benefits under full operational conditions.

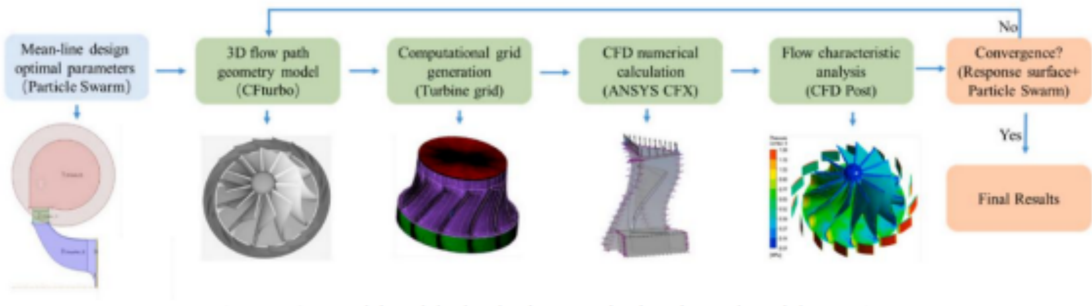

Figure 8. Turbine blade design optimization algorithm.

Flexibility and Load Adaptation

The studies by Rashid et al. (2021) and Wang & Lee (2020) emphasize the growing need for dynamic load adaptation in modern energy systems, where power demand frequently fluctuates. The application of exergy-based control systems provides promising results in mitigating part-load efficiency losses. This implies that control system innovation, alongside mechanical improvements, is critical in achieving optimal turbine operation under real-world variability.

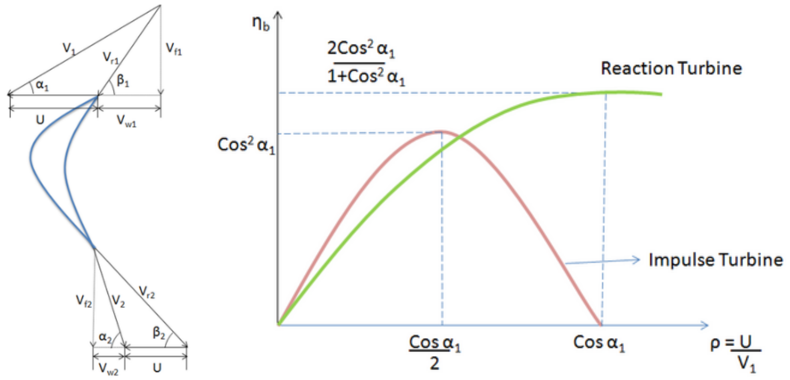

Figure 9. a. Speed triangle, b. Comparing the Efficiency of Impulse and Reaction Turbines

Renewable and Hybrid Integration

With the global transition toward sustainability, the incorporation of steam turbines in hybrid systems (solar, biomass) has become a promising pathway. Kim & Park (2020) and Al-Mahmoud et al. (2022) highlighted that such configurations not only boost output but also reduce greenhouse gas emissions. Nonetheless, integrating variable renewable sources requires advanced control and thermal storage strategies to maintain system stability.

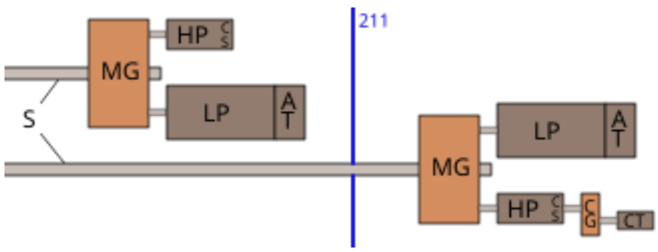

Figure 10. The starboard steam turbine engine arrangement of the Japanese Furutaka and Aoba class cruisers

Manufacturing and Maintenance Innovation

The advancement of additive manufacturing (Müller & Köhler, 2023) and the implementation of IoT-based predictive maintenance (Gupta & Mehta, 2021) indicate a broader digital transformation within steam turbine systems. The ability to detect failures early and reduce unplanned outages contributes significantly to reducing life-cycle costs and enhancing operational safety. However, the economic feasibility and cybersecurity concerns related to IoT systems require further investigation.

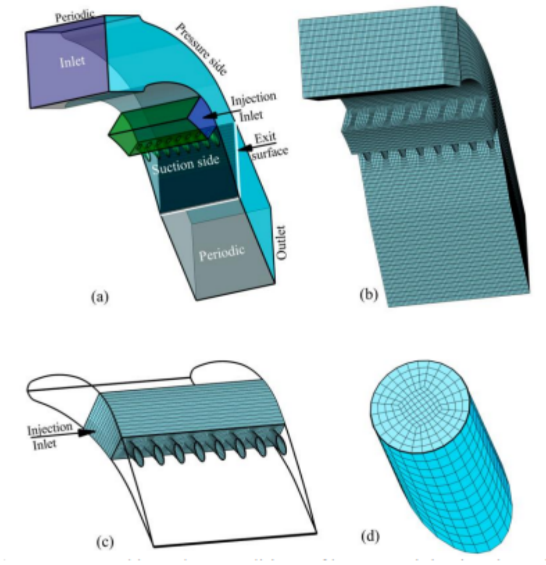

Figure 11. (a) Geometry and boundary conditions of hot steam injection through embedded channels, (b) blade grid, (c) channel grid, and (d) O-grid in HSI (Hot Steam Injection Hole).

Theoretical vs Practical Gaps

While many studies use powerful simulation techniques, one limitation identified is the lack of experimental or in-field validation. Several promising models and design proposals remain untested under real power plant conditions. This raises concerns regarding scalability and reliability, which must be addressed in future research efforts.

Implications for the Energy Sector

The findings in this study reaffirm that steam turbines will likely continue to play a vital role, particularly as part of flexible, hybridized energy systems. Innovations in design, materials, control systems, and maintenance practices collectively contribute to making steam power more efficient and sustainable. In developing countries, especially, the improved cost-effectiveness and durability of newer turbines could provide reliable baseload power while supporting decarbonization goals.

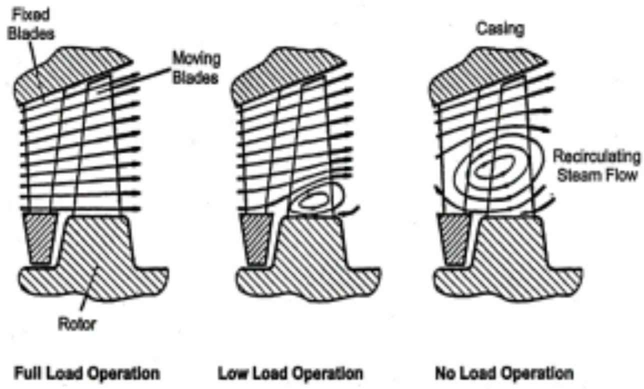

Figure 12. Partial load conditions at turbine blade

CONCLUSION

This study reviewed ten recent international journal articles focusing on the performance, efficiency, and technological development of steam turbines within the context of modern energy systems. The findings reveal that steam turbines, despite being a mature technology, are experiencing renewed innovation through advanced simulation tools (such as CFD and FEA), improved materials, and enhanced control systems. These developments have led to measurable gains in thermal efficiency, reliability, and adaptability, especially in hybrid energy systems involving renewable sources like solar and biomass.

Table 3. Summary of Key Conclusions and Research Implications

Aspect	Summary
Main Findings	Steam turbines continue to improve through simulation, materials, and control strategies.
Technological Advances	CFD, FEA, AI-based models, Inconel alloys, IoT-based maintenance, hybrid systems.
Efficiency Impact	Gains range from 2% to 7.3% in thermal efficiency depending on optimization method.
Key Limitations	Lack of real-world validation, limited tropical/regional studies, economic data gaps.
Future Research Focus	Experimental validation, lifecycle cost analysis, integration in hybrid renewable grids.

In addition to performance optimization, the reviewed literature highlights the growing role of digitalization through IoT-based predictive maintenance and additive manufacturing in reducing operational costs and improving reliability. However, the lack of standardized experimental validation and real-world implementation remains a critical challenge. Future research should focus on bridging the gap between simulation and actual operational performance, enabling broader deployment of high-efficiency steam turbines in both industrialized and developing energy sectors.

LIMITATION

Although this study provides a comprehensive review of recent advancements in steam turbine technology, it is limited by the scope and number of selected articles. Only ten journal articles published within the last five years were analyzed, which may not fully represent the complete breadth of ongoing global research in this field. Some potentially relevant studies might have been excluded due to language constraints (English-only) or limited database access.

Another limitation lies in the inherent nature of a literature-based study, which relies solely on secondary data from previously published research. While simulation results and proposed design improvements were extensively discussed in the reviewed papers, most lacked real-world validation or long-term performance data from operational steam power plants. This creates a gap between theoretical potential and practical implementation, which may affect the generalizability of the findings.

Lastly, the review does not comprehensively account for regional or environmental variations, such as turbine performance in tropical or high-humidity climates, which may significantly influence thermal efficiency and material durability. Additionally, economic feasibility analyses, cost-benefit comparisons, and lifecycle assessments were not deeply explored in the selected studies. These factors, if investigated further, would provide a more holistic understanding of the challenges and opportunities in deploying next-generation steam turbine technologies.

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