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Evaluation Turbine Blade Design and Materials Steam Power Plant : *Literature Review*

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ABSTRAK

Bilah turbin merupakan komponen krusial pada PLTU yang secara langsung mempengaruhi efisiensi termal dan keandalan sistem. Penelitian ini bertujuan untuk melakukan kajian sistematis terhadap desain dan kegagalan bilah turbin menggunakan pendekatan kajian pustaka sistematis (SLR) yang meliputi empat klasifikasi utama, yaitu Desain dan Optimasi, Material dan Analisis Struktur, Analisis dan Prediksi Kegagalan, serta Aerodinamika dan Aliran Uap. Hasil penelitian menunjukkan bahwa optimasi desain bilah menggunakan metode numerik seperti Computational Fluid Dynamics (CFD), algoritma genetika, dan metode Taguchi dapat mengurangi kehilangan energi secara signifikan, seperti mengurangi kehilangan kondensasi hingga 28,5% dan mengurangi laju erosi hingga 58%. Material berkekuatan tinggi, seperti Waspaloy, telah terbukti efektif untuk aplikasi bertekanan tinggi, sementara teknologi pengerasan permukaan seperti pengerasan laser dan shot peening meningkatkan kekerasan dan ketahanan lelah bilah. Selain itu, analisis kegagalan menggunakan teknik getaran dan metode Metal Magnetic Memory (MMM) memungkinkan deteksi dini kerusakan untuk mencegah kegagalan besar. Studi ini menyimpulkan bahwa kombinasi teknik optimasi multi-objektif, pemantauan waktu nyata, dan pengembangan material canggih dapat meningkatkan efisiensi energi dan keberlanjutan pembangkit listrik tenaga uap..

Kata kunci*: efisiensi termal, desain dan optimasi, analisis kegagalan, aerodinamika, pembangkit listrik tenaga uap.*

ABSTRACT

Turbine blades are critical components in a steam power plant that directly affect the thermal efficiency and reliability of the system. This study aims to conduct a systematic review of turbine blade design and failure using a systematic literature review (SLR) approach that covers four main classifications, namely Design and Optimization, Materials and Structural Analysis, Failure Analysis and Prediction, and Aerodynamics and Steam Flow. The results of the study show that blade design optimization using numerical methods such as Computational Fluid Dynamics (CFD), genetic algorithms, and the Taguchi method can significantly reduce energy losses, such as reducing condensation losses by up to 28.5% and reducing erosion rates by up to 58%. High-strength materials, such as Waspaloy, have proven effective for high-pressure applications, while surface hardening technologies such as laser hardening and shot peening increase the hardness and fatigue resistance of the blades. In addition, failure analysis using vibration techniques and the Metal Magnetic Memory (MMM) method allows early detection of damage to prevent major failures. This study concludes that the combination of multi-objective optimization techniques, real-time monitoring, and advanced material development can improve the energy efficiency and sustainability of steam power plants.

Keywords: thermal efficiency, design and optimization, failure analysis, aerodynamics, steam power plant.

1. Introduction

Thermal efficiency and turbine performance depend heavily on the design, material and operational conditions of the turbine blades. **[1]**. The main problems faced in turbine blade design include efficient steam flow control to maximize energy conversion, reduction of energy losses due to condensation causing droplet formation, and mitigation of erosion and material fatigue arising from high thermal and mechanical stresses. **[2-4]** . Suboptimal blade geometry design can induce flow turbulence, increase friction, and reduce effective energy transfer **[5]**. In addition, blade materials that are not resistant to high temperatures and corrosion can cause cracks and premature failure requiring expensive maintenance and replacement **[6-9]**. Therefore, comprehensive research is needed to find the right design and material solutions to maximize performance and extend the service life of turbine blades.

Based on previous studies, there are various focuses of studies on turbine blade design and failure, which directly affect the efficiency and performance of power plants. Chowdhury et al. (2023) reviewed the cooling performance and failure analysis of gas turbine blades, emphasizing the importance of selecting appropriate working fluids, fuel composition, and modern cooling systems that can support high-temperature operations above 1600°C **[10]**. On the other hand, Puspitasari et al. (2021) provide an in-depth analysis of turbine blade failure mechanisms, such as fatigue, creep, oxidation, corrosion, and erosion, as well as the need for improved analysis to improve the reliability of this critical component **[11]**. Furthermore, a study by Živković et al. (2024) highlighted the factors causing vibrations in steam turbines, including unbalance, misalignment, and rotor fatigue cracks, which can damage turbine performance. This study also emphasized the importance of proper maintenance and thorough monitoring of the entire turbine assembly to prevent operational disruptions **[12]**. On the other hand, Omojogberun et al. (2024) provided an analysis related to the three main components of a steam turbine, including: blades, rotors, and bearing characteristics. This study also emphasizes the importance of determining the design and mapping of the forces that occur in the turbine blades **[13]** . However, in these studies, there has been no literature review that specifically discusses the development of design optimization, material selection, flow patterns and structural analysis of turbine blade components against energy losses in steam power plants.

The objective of this study is to review and synthesize the current literature on turbine blade design and failure in the context of energy losses in thermal power plants comprehensively covering design optimization, materials, failure analysis and blade flow patterns . Through this review, various approaches such as numerical simulation, experimental analysis, and design optimization will be evaluated to identify best practices and current technologies that can improve turbine blade performance. The main focus is to understand the interaction between blade design, operational conditions, and materials used in an effort to minimize energy losses and extend the life of turbine blades.

The scope of this review focuses on steam turbine blades in Rankine cycle power plants, without covering other types of turbines such as gas turbines or wind turbines. In addition, this study only includes studies that use data-driven approaches such as CFD simulations, FEM analysis, and material testing. Studies that are theoretical or do not have comparable quantitative data are excluded from this review. Through these limitations, it is hoped that this literature review can provide a comprehensive overview of design innovations and failure analysis of turbine blades in steam power plants that are relevant and applicable.

2. Method

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 is 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. The data search steps are shown in Figure 1.

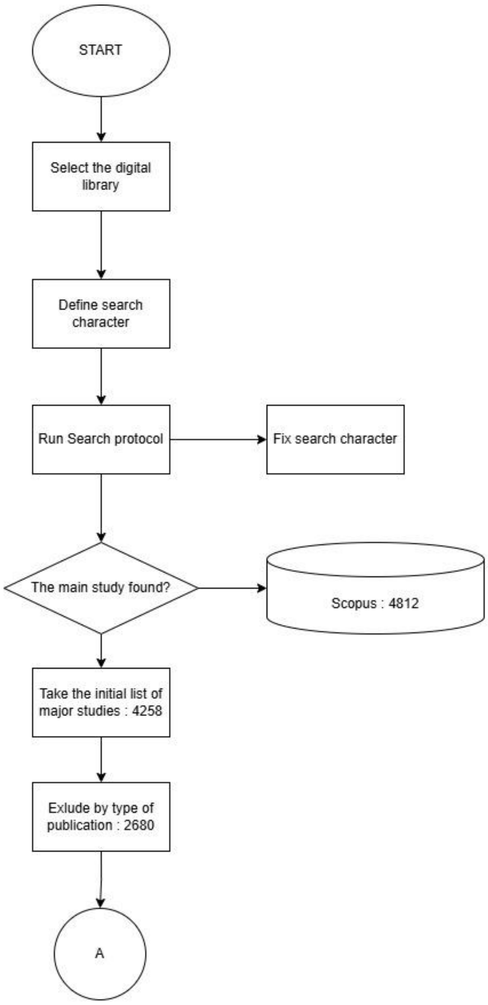

Figure 1. Flow diagram of the data search stage

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 in-depth and evidence-based technical recommendations to improve the efficiency and service life of turbine blades in steam power plants.

2.1. *State of the art* Research

In this study, the reviewed articles are classified into four main categories, namely Design and Optimization, Materials and Structural Analysis, Failure Analysis and Prediction, Aerodynamics and Vapor Flow. The state of the art table is shown in Table 2 .

Table 2. State of the art research.

Classification	Research Topics	Author	Publish Year	Methodology	Key Findings
Design and Optimization	Design and optimization of slot number in supercooled vapor suction	Hosseini et al.	2024	CFD simulation, TOPSIS method, Eulerian-Eulerian model	Reduction of condensation losses by up to 6% and droplets by up to 25% **[14]**
	Optimization design of radial inflow turbine using CFD analysis	Li et al.	2024	1D mean-line model and CFD simulation	Total-static efficiency increased from 88.5% to 91.7% **[15]**
	Hot steam injection through embedded channels	Ghodrati et al.	2023	Two-phase flow simulation with steam injection	Erosion reduction of up to 58% and condensation losses of up to 28.5% **[16]**

Classification	Research Topics	Author	Publish Year	Methodology	Key Findings
	Optimization of a novel impulse gas turbine nozzle	Liaw et al.	2023	Taguchi method, CFD simulation, geometry optimization	Power increase up to 4928.64W with 64.65% efficiency **[17]**
Materials and Structural Analysis	Structural and thermal analysis of high-pressure turbine blades	Prabha et al.	2023	FEM simulation, thermal and structural analysis	Waspaloy has the best resistance to thermal deformation **[18]**
	Laser hardening and shot peening for stress reduction	Pavan et al.	2024	Laser hardening, residual stress measurement by XRD	Increased hardness of ~ 2.75 mm from the surface and mitigation of residual stress **[19]**
Failure Analysis and Prediction	Fatigue fracture failure analysis of 12Cr12Mo turbine blade	He et al.	2023	Mechanical fatigue analysis and electron microscopy	Cracks are caused by high gamma-ferrite in the material **[20]**
	Damage evaluation using vibration analysis	Graciano et al.	2023	Vibration analysis, dynamic testing, natural frequency method	Early crack detection through natural frequency changes **[21]**
	Frequency and mode shape evaluation using MMM method	Rockiki et al.	2023	Magnetic field analysis, operating frequency measurement	Early diagnostics through magnetic field distribution analysis **[22]**
	Vibration characteristics and life prediction in steam turbines	Hu et al.	2024	Vibration simulation, wet steam model	Identification of critical points of the blade through stress distribution **[23]**
Aerodynamics and Steam Flow	Droplet-wall interaction simulation	Hu et al.	2023	Wet steam model, two-phase flow simulation	The maximum displacement is higher in the wet steam model **[24]**
	Optimization of operating conditions in turbine blade cascade	Sadrian et al.	2023	Genetic algorithm, CFD simulation	Reduction of liquid mass fraction up to 32% and droplets up to 29% **[25]**

Based on the articles reviewed in the state of the art table, the four categories reflect key aspects that interact with each other in the development and operation of steam power plant turbine blades. Each category includes elements that are essential in improving the efficiency, reliability, and operational life of the turbine.

3. Evaluation

3.1. Turbine Blade Design Optimization

Optimal turbine blade design contributes significantly to increasing energy efficiency. Hosseini et al. (2024) showed that optimizing the configuration of suction slots on turbine blades reduces condensation losses by up to 6% and reduces droplet size by up to 25% **[26]**. The simulation was performed using an Eulerian-Eulerian model that models two-phase flow by considering pressure control and steam flow , the steam nucleation zone scheme of the turbine blade is shown in **Figure 2.** This approach is effective because the more controlled steam flow arrangement reduces friction and uneven pressure distribution on the blades.

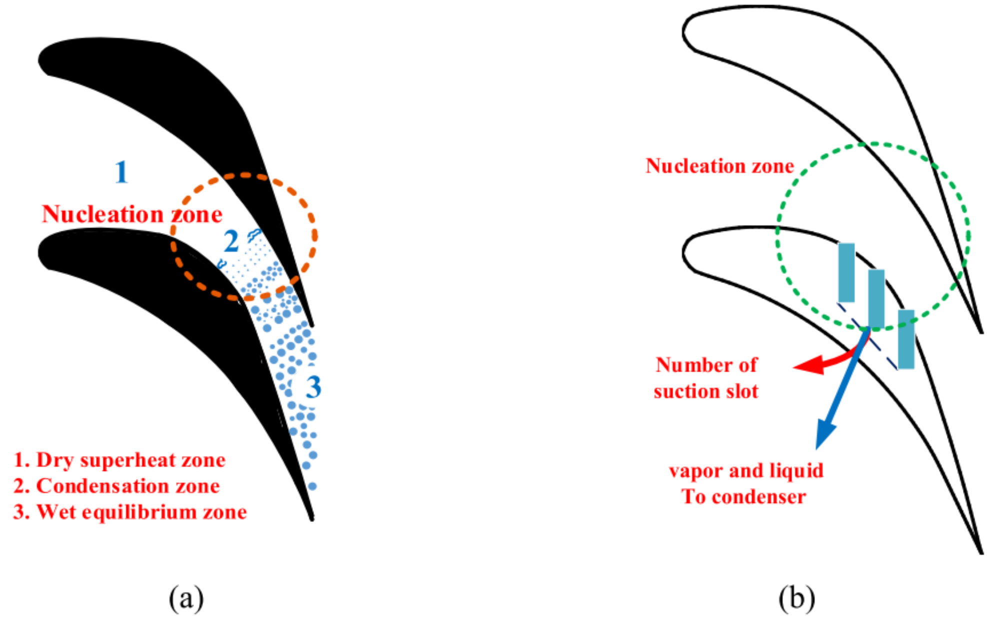

Figure 2. (a) Mechanism of nucleation zone and steam flow in turbine blades; (b) Mechanism of suction slot in stationary turbine blades. **[14]**

Li et al. (2024) used a combination approach of 1D mean-line design and CFD simulation to improve the efficiency of a radial flow turbine from 88.5% to 91.7%. They reduced the friction and turbulence losses inside the turbine duct by utilizing a numerical model-based optimization algorithm. This shows that optimizing the turbine geometry at an early design stage can result in significant efficiency improvements before experimental testing is performed. The optimization algorithm is shown in **Figure 3** .

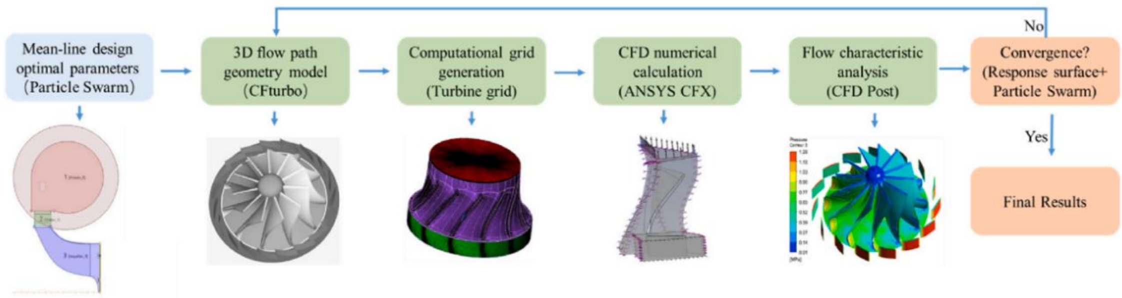

Figure 3. Turbine blade design optimization algorithm. **[15]**

Meanwhile, Ghodrati et al. (2023) showed that hot steam injection through embedded channels reduced erosion by 58% and condensation losses by 28.5%. This reduction was achieved by keeping the blade surface dry, which also minimized turbulence and kinetic energy loss. These results emphasize the importance of controlling temperature and humidity in the turbine blade flow space to reduce the destructive effects of condensation. The hot steam injection design is shown in **Figure 4** .

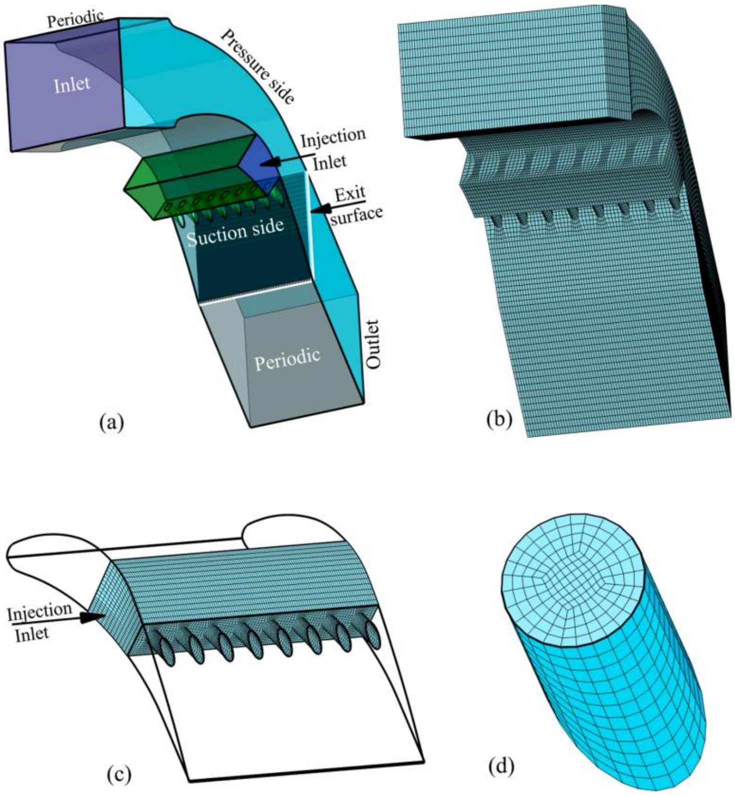

Figure 4. (a) Geometry and boundary conditions of hot steam injection through embedded channels, (b) blade grid, (c) channel grid, and (d) O-grid in HSI (Hot Steam Injection Hole). **[16]**

These findings show that turbine blade design is not only a geometric problem, but also involves complex steam flow control. The use of CFD simulation and optimization algorithms allows for more precise design settings, which ultimately minimize energy losses and improve efficiency. Design optimization needs to be accompanied by thermal and pressure control so that the results obtained from the simulation can be applied practically.

3.2. Turbine structure and material analysis

Turbine blade materials must have good resistance to high temperatures, high pressures, and corrosive environments. Aruna Prabha et al. (2023) found that Waspaloy has the best thermal and fatigue resistance compared to materials such as ATI 720 Alloy and Inconel 725 , the test results are shown in Table 3. This material shows superior performance under high operating conditions due to its thermal stability and creep resistance.

Table 3. Comparison of material performance in turbine blades.

Material	Total Deformation (mm)	Equivalent Strain (m/m)	Equivalent Stress (MPa)
Incoloy 903	0.11	0.0008	100
ATI 720 Alloy	0.02	0.0002	10
Wasp Alloy	0.085	0.00058	100
Mo TZM Molybdenum Alloy	0.06	0.00041	140
Inconel 725	0.01	0.00062	118

However, Pavan et al. (2024) found that laser hardening increases the surface hardness of the blade up to ~ 2.75 mm from the surface , but also creates tensile residual stresses that trigger potential cracks. By applying the shot peening process after laser hardening, these residual stresses are successfully compressed, extending the service life of the turbine blade by increasing the resistance to surface cracks. Residual stress mapping of the turbine blade after laser hardening is shown in Fig. and residual stress mapping of the turbine blade after laser hardening and shot peening treatment is shown in Fig. 5.

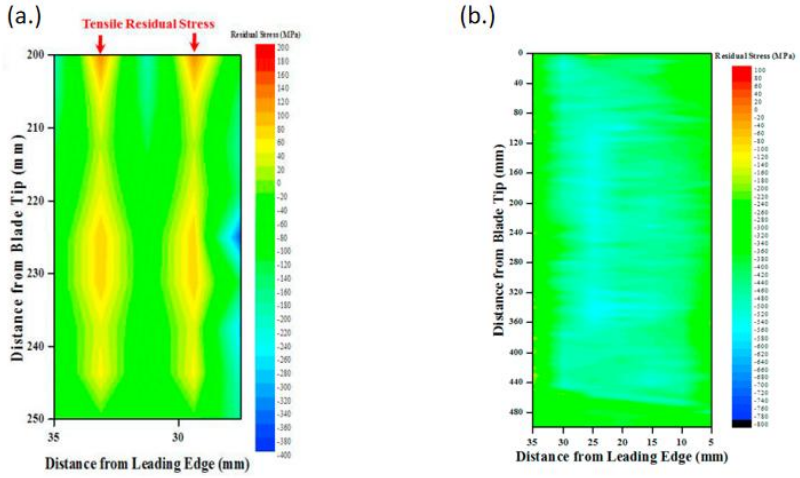

Figure 5. (a) Residual stress map on the blade without the blade profile shot peening process (b) Residual stress map on the blade without the blade profile shot peening process **[19]**

These findings highlight the importance of combining high-performance materials with appropriate surface treatment processes. Materials such as Waspaloy provide high-temperature resistance, but to improve erosion resistance, additional treatments such as laser hardening and shot peening are required. This suggests that material selection and treatment techniques should be planned together at the manufacturing stage.

3.3. Failure Analysis and Life Prediction

Failure analysis of turbine blades includes studies on fatigue, material cracking, and failure due to thermal and mechanical cycling. He et al. (2023) found that high gamma-ferrite content in 12Cr12Mo material causes a decrease in fatigue strength and rapid crack propagation, especially at high temperatures , the test results on Blade 1 which has 10% gamma-ferrite and Blade 2 which has 1-2% gamma ferrite are shown in Figure 6.

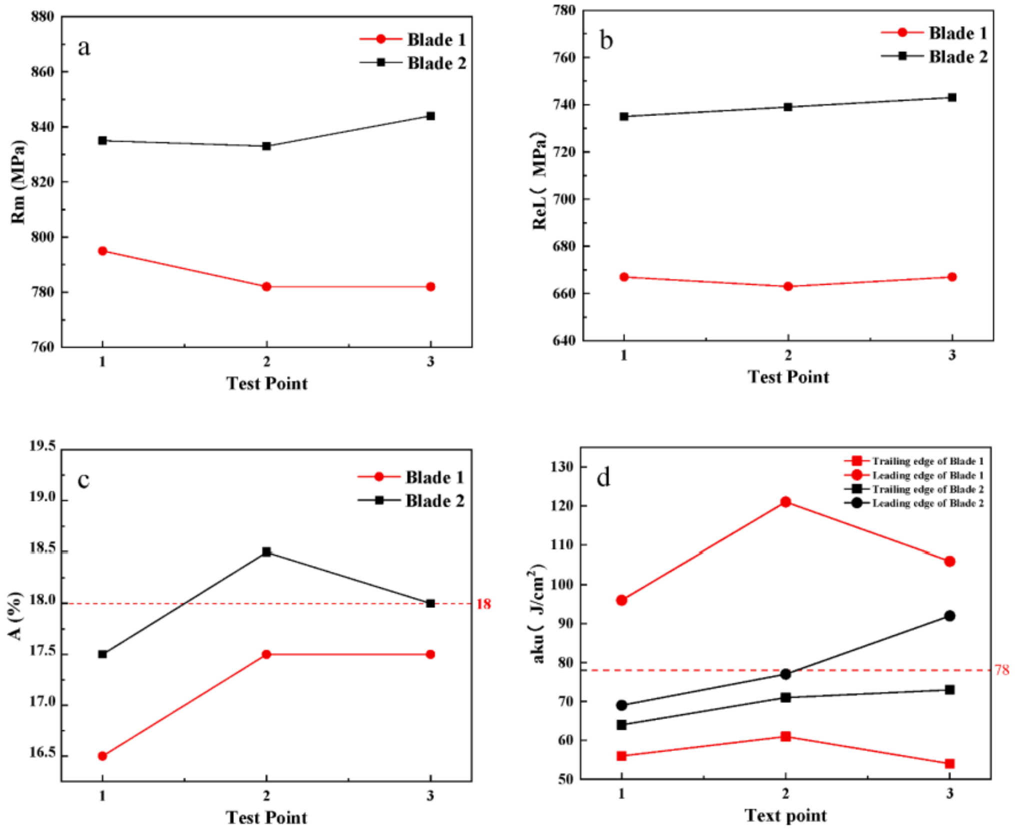

Figure 6. Results of mechanical property tests (a) tensile strength value (b) yield strength value (c) elongation after fracture (d) impact toughness value. **[20]**

For enhancing the quality of identification without relying on FEM and costly experimental testing, the Metal Magnetic Memory (MMM) to detect the frequency and shape of turbine blade operating modes, enabling a more efficient identification of potential failures **[22]**. The magnetic measurement scheme is shown in Figure 7.

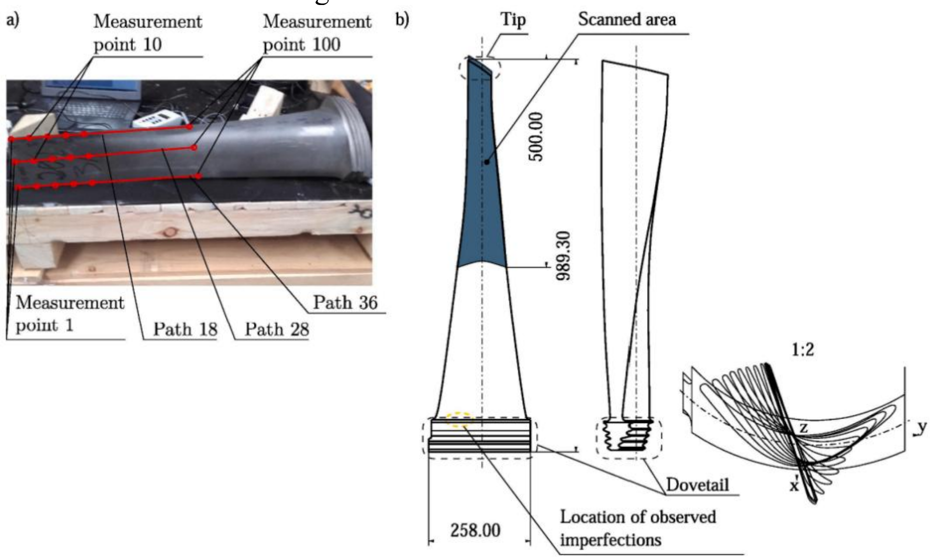

Figure 7. Scheme of magnetic field measurement with GM08 magnetometer: a) measurement mesh, b) blade geometry **[22]**.

In addition, Hu et al. (2024) conducted a vibration analysis using a wet steam model to predict the vibration mode characteristics and critical points of the last blade of a 600 MW turbine, allowing for better failure prevention measures.

Graciano et al. (2023) showed that changes in the natural frequency of turbine blades can detect cracks at an early stage. With vibration analysis and dynamic parameter monitoring, early damage can be detected before it leads to total failure, allowing for preventive repair actions.

The relationship between material composition, manufacturing process and monitoring methods is very clear. High-quality materials need to be supported by real-time monitoring techniques to detect potential damage early. This combination allows for reduced turbine downtime and extended service life of key components.

3.4. Aerodynamics and Steam Flow Analysis of Turbine Blades

Steam flow aerodynamics plays an important role in maximizing turbine efficiency. Sadrian et al. (2023) used a blackbox algorithm shown in Figure 8. to optimize the stagnation temperature and pressure ratio at the turbine blades, resulting in a reduction in liquid mass of up to 32% and a reduction in droplet size of up to 29%.

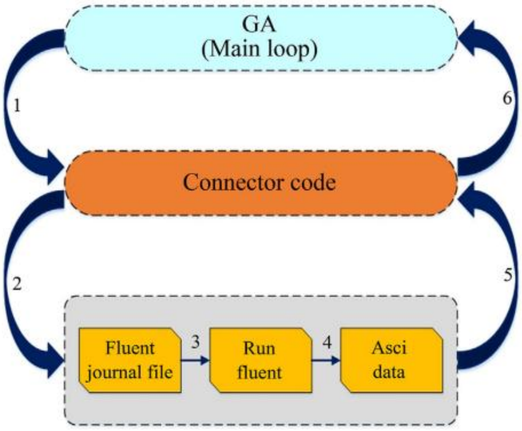

Figure 8. Flowchart of the black-box optimization process consisting of three blocks: GA (main part), Connector code, and Fluent **[25]**.

Hu et al. (2023) showed that the wet vapor model produces higher circumferential force and maximum displacement compared to the ideal gas model , the graph is shown in Figure 9. This proves the importance of considering the effects of droplet interactions in aerodynamic design to reduce energy losses.

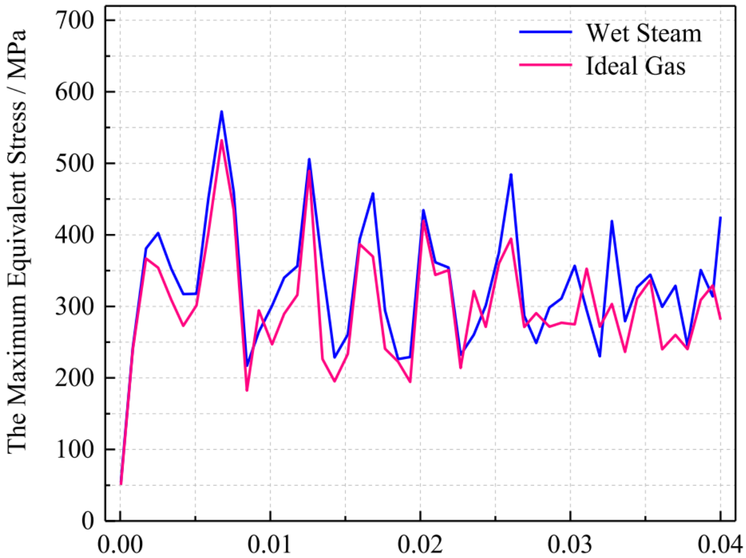

Figure 9. Comparison of Maximum Equivalent Stress against time at THA (Turbine Heat Acceptance) conditions for Wet Steam and Ideal Gas **[24]**.

The relationship between blade geometry and vapor flow parameters is very close. Aerodynamic optimization should include control of pressure, temperature, and humidity levels to make the blade design more resistant to droplet formation and energy loss **[27-28]**.

3.5 Advantages and Limitations of the Study

Based on the data analyzed in this literature study, several advantages and limitations can be highlighted. In terms of advantages, this study successfully identifies various innovative approaches in turbine blade design and analysis, including geometric optimization through numerical methods such as Computational Fluid Dynamics (CFD), genetic algorithms, and the Taguchi method. Additionally, it reveals the effectiveness of thermally and fatigue-resistant materials, such as Waspaloy, as well as turbine blade durability enhancement techniques through laser hardening and shot peening. The application of failure prediction methods, such as vibration analysis and the Metal Magnetic Memory (MMM) method, also provides valuable insights for early damage detection, thereby extending the lifespan of turbine components.

However, there are certain limitations in this literature review. One of the main drawbacks is the lack of experimental data to support the effectiveness of the reviewed methods, as most studies remain theoretical or rely on numerical models. Moreover, many studies focus on specific aspects without integrating various factors that influence turbine blade efficiency and durability comprehensively. For example, while aerodynamic analyses have been extensively conducted, a multidisciplinary approach that combines thermal, mechanical, and material considerations is still required to achieve a more holistic understanding. Furthermore, challenges remain in implementing real-time monitoring technologies and AI-based optimization, which require further research. Therefore, this review serves as a foundation for future studies in developing more integrated and applicable solutions to enhance the efficiency and sustainability of steam power plant systems.

4. Conclusion

Based on a literature review on turbine blade design and failure in steam power plants, various innovative approaches have been successful in improving thermal efficiency and extending the lifespan of turbine components. Research shows that optimizing turbine blade design through numerical methods such as Computational Fluid Dynamics (CFD), genetic algorithms, and Taguchi methods can significantly reduce energy losses. The optimization of suction and injection slot geometry in steam flow has proven to be particularly effective, reducing condensation losses by up to 28.5% and minimizing erosion rates by 58%. These findings highlight the importance of precise aerodynamic design in mitigating energy dissipation and enhancing turbine performance.

Materials with high resistance to thermal deformation and fatigue, such as Waspaloy, have been identified as highly effective for high-pressure turbine applications. Advances in surface treatment techniques, including laser hardening and shot peening, have further improved the durability of turbine blades by increasing surface hardness. However, these improvements must be carefully managed to control residual stresses that could lead to premature cracking. The selection and treatment of materials thus play a critical role in ensuring the long-term reliability of turbine components, balancing mechanical strength with resistance to operational wear and tear.

In the aspect of failure analysis, damage detection and blade life prediction have been significantly enhanced by advanced diagnostic techniques. Methods such as vibration analysis, Metal Magnetic Memory (MMM), and finite element modeling provide deeper insights into stress distributions and early-stage crack formation. Detecting cracks through variations in natural frequencies and stress patterns has proven to be an effective preventive measure, allowing for timely maintenance and reducing the risk of catastrophic failures. The integration of these diagnostic tools into turbine maintenance strategies is essential for extending component lifetimes and minimizing unexpected downtimes.

Overall, research on turbine blade design and failure continues to progress toward the development of more efficient and durable turbines. Future challenges include the integration of multi-objective optimization techniques that simultaneously address efficiency, durability, and cost-effectiveness. The application of real-time monitoring systems and the development of advanced materials will be crucial in maximizing turbine performance while minimizing operational costs. By combining numerical simulations, experimental validations, and real-time diagnostics, a more comprehensive and sustainable approach can be achieved, ultimately enhancing the efficiency and longevity of steam power plants.

4.1 Suggestions

Based on the results of the systematic review that has been conducted, several recommendations can be given for further research and development related to the design and failure of turbine blades in steam power plants. First, future research needs to focus more on the development of multi-objective optimization techniques that can consider various parameters simultaneously, such as thermal efficiency, material durability, and production costs. The combination of numerical methods such as Computational Fluid Dynamics (CFD) with artificial intelligence (AI)-based algorithms can be a promising approach. In addition , the exploration of new materials with better resistance to thermal deformation, fatigue, and corrosion, such as ceramic-based alloys or amorphous metals, needs to be increased. The use of these advanced materials should be balanced with the development of more efficient and economical manufacturing methods.

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