

Data-Driven Thermo-Structural Optimization of Gas Turbine Blades Using Finite Element Modeling, Cooling Configurations, and Thermal Barrier Coatings

“Thermo-Structural Optimization of Gas Turbine Blades Using FEA and Film Cooling

Syed Eirfan Atthar* and Nilomjyoti Saikia

Department of Mechanical Engineering (Thermal & Fluid), Dibrugarh University (DUIET), Assam, 786001, India

*Corresponding authors

Syed Eirfan Atthar, Department of Mechanical Engineering (Thermal & Fluid), Dibrugarh University (DUIET), Assam, 786001, India.

Received: July 21, 2026; **Accepted:** August 25, 2026; **Published:** September 26, 2026

Abstract

Gas turbine blades operate under extremely severe thermo-mechanical environments characterized by elevated turbine inlet temperatures, high centrifugal forces, thermal gradients, oxidation, and cyclic loading conditions. Continuous improvements in gas turbine efficiency have significantly increased turbine inlet temperatures beyond the thermal capability of conventional metallic materials, thereby necessitating the development of advanced cooling strategies and thermal protection systems. Among the available cooling approaches, film cooling combined with Thermal Barrier Coatings (TBCs) has emerged as one of the most effective techniques for reducing blade surface temperature and improving operational durability. However, the simultaneous interaction between cooling-hole configuration, material selection, thermal resistance, and coating-induced stresses introduces complex thermo-structural challenges that require detailed numerical investigation. Existing studies primarily focus on isolated thermal or structural analyses, while limited research has integrated data-driven thermo-structural optimization with comparative evaluation of cooling configurations and coating systems under realistic operating conditions.

The present study investigates the thermo-structural performance of gas turbine blades using finite element analysis (FEA) under different cooling configurations and material selections. Three substrate materials, namely Inconel 718, N-155 alloy, and Chromium Steel, were analysed using ANSYS Workbench under steady-state thermal and structural loading conditions. Film cooling was modelled using 5-hole, 9-hole, and 13-hole radial cooling configurations. Furthermore, a two-layer Thermal Barrier Coating system consisting of a 250 μm Yttria-Stabilized Zirconia (YSZ) top coat and a 100 μm MCrAlY bond coat was incorporated to evaluate coating effectiveness and interfacial stress behavior. Thermo-fluid calculations, stress analysis, and heat-transfer modelling were coupled with statistical interpretation of simulation outputs to establish a data-driven optimization framework for turbine blade cooling performance. The results indicate that Inconel 718 exhibits superior thermal resistance and structural stability compared to N-155 and Chromium Steel.

The 5-hole cooling configuration demonstrated the lowest heat flux values, indicating optimum cooling effectiveness before the onset of diminishing thermal returns associated with excessive cooling-hole density. The incorporation of TBC layers reduced substrate temperature significantly while simultaneously introducing localized interfacial stresses due to thermal expansion mismatch. Comparative analysis revealed that the combined application of Inconel 718 substrate material, optimized film cooling, and ceramic TBC protection provides enhanced thermal protection, reduced deformation, lower von Mises stress, and improved service life for high-temperature turbine applications. The proposed data-driven thermo-structural optimization framework provides valuable engineering insights for the design of next-generation gas turbine cooling systems and advanced thermal management strategies.

Keywords: Gas Turbine Blade, Finite Element Analysis, Thermal Barrier Coating, Film Cooling, Thermo-Structural Analysis, Heat Flux Optimization, Inconel 718, Ansys Workbench, Turbine Cooling, Thermal Stress, Data-Driven Optimization, High-Temperature Materials

Citation: Syed Eirfan Atthar, Nilomjyoti Saikia. Data-Driven Thermo-Structural Optimization of Gas Turbine Blades Using Finite Element Modeling, Cooling Configurations, and Thermal Barrier Coatings “Thermo-Structural Optimization of Gas Turbine Blades Using FEA and Film Cooling. J Supply Chain Manag Smart Netw. 2026. 1(2): 1-22. DOI: doi.org/10.61440/JSCMSN. 2026.v1.07

Introduction

The increasing global demand for efficient power generation and advanced aerospace propulsion systems has accelerated the development of high-performance gas turbine technologies [1,2]. Gas turbines are extensively employed in aircraft engines, thermal power plants, marine propulsion systems, and industrial energy-generation applications due to their high power-to-weight ratio, compact design, rapid startup capability, and operational efficiency [3]. One of the primary methods for improving gas turbine efficiency involves increasing the turbine inlet temperature (TIT), since higher operating temperatures directly enhance thermal efficiency according to Brayton cycle principles [4,5].

Over the past several decades, turbine inlet temperatures have increased from nearly 800 K in early turbine systems to values exceeding 1700 K in modern advanced gas turbines [6]. However, such elevated operating temperatures impose severe thermo-mechanical loads on turbine blade materials, often approaching or exceeding their metallurgical limits. Gas turbine blades operate under extremely hostile environments characterized by high thermal gradients, centrifugal forces, cyclic loading, oxidation, creep deformation, thermal fatigue, and aerodynamic stresses [7,8]. The leading edge of turbine blades is particularly vulnerable due to stagnation heating effects and direct exposure to high-temperature combustion gases [9]. Prolonged exposure to such conditions can result in crack initiation, coating delamination, creep failure, thermal distortion, and eventual catastrophic blade failure [10].

Consequently, efficient thermal management and structural reliability of turbine blades have become critical research areas in modern turbomachinery engineering. To overcome these challenges, several advanced blade cooling technologies have been developed, including internal convection cooling, film cooling, impingement cooling, transpiration cooling, and hybrid cooling systems [11,12]. Among these techniques, film cooling has emerged as one of the most effective approaches for reducing blade surface temperature. In film cooling, relatively cooler air extracted from the compressor is injected through small holes onto the blade surface, forming a protective insulating layer that minimizes direct exposure of the blade material to hot combustion gases [13]. The geometry, orientation, diameter, and number of cooling holes significantly influence cooling effectiveness, local heat transfer characteristics, and aerodynamic performance [14]. Although increasing the number of cooling holes may improve local cooling, excessive perforation can weaken the structural integrity of the blade and generate undesirable stress concentrations [15]. Therefore, identifying an optimum cooling-hole configuration remains an important engineering challenge. In addition to cooling technologies, Thermal Barrier Coatings (TBCs) are extensively employed to improve the thermal durability of turbine components operating under elevated temperatures [16]. TBC systems generally consist of a ceramic top coat, typically Yttria-Stabilized Zirconia (YSZ), deposited over a metallic bond coat such as MCrAlY [17].

The ceramic layer possesses low thermal conductivity and acts as an insulating barrier, thereby reducing heat transfer to the metallic substrate [18]. This reduction in substrate temperature improves creep resistance, oxidation resistance, and overall component

life. However, the mismatch in coefficients of thermal expansion (CTE) between the ceramic coating and metallic substrate introduces significant interfacial stresses during thermal cycling [19]. Repeated thermal loading can result in coating spallation, crack propagation, and delamination, thereby reducing coating durability and long-term reliability [20]. Hence, a detailed thermo-structural assessment of TBC-coated turbine blades is essential for developing reliable high-temperature turbine systems. Several researchers have investigated turbine blade cooling and coating technologies using experimental methods, computational fluid dynamics (CFD), and finite element analysis (FEA) [21,22].

Finite element methods have gained considerable importance because they allow detailed evaluation of temperature distribution, thermal stresses, deformation, heat flux, and structural behavior under complex loading conditions [23]. ANSYS-based thermo-structural simulations have been widely adopted for predicting blade performance and identifying critical stress zones [24]. Nevertheless, most existing studies focus either on thermal analysis or structural analysis independently, while only limited investigations have integrated cooling-hole optimization, material comparison, TBC performance, and data-driven interpretation within a unified thermo-structural framework [25,26]. Modern turbine engineering increasingly relies on data-driven numerical optimization approaches rather than purely experimental trial-and-error methods [27]. The integration of statistical interpretation with finite element simulations enables improved understanding of thermal trends, cooling effectiveness, stress redistribution, and material behavior under varying operating conditions [28]. Such approaches provide deeper engineering insights for identifying optimum cooling configurations and material.

Combinations capable of maximizing thermal efficiency while maintaining structural reliability. In this context, the present study performs a comprehensive thermo-structural finite element investigation of gas turbine blades considering different cooling configurations, substrate materials, and Thermal Barrier Coating systems. Three commonly used turbine materials, namely Inconel 718, N-155 alloy, and Chromium Steel, are comparatively analyzed using steady-state thermal and structural simulations in ANSYS Workbench. Film cooling is modeled using multiple radial cooling-hole configurations, while TBC effectiveness is evaluated using a YSZ-MCrAlY coating system. In addition, a data-driven interpretation of simulation outputs is incorporated to identify optimum cooling performance and establish a thermo-structural optimization framework for advanced gas turbine blade applications.

Research Gap and Problem Identification

The continuous advancement of gas turbine technology has led to a substantial increase in turbine inlet temperatures in order to achieve higher thermal efficiency and improved power output [1,2]. Although advanced superalloys and cooling technologies have significantly enhanced turbine blade durability, turbine blades continue to operate under severe thermo-mechanical environments involving elevated temperatures, high centrifugal stresses, thermal fatigue, oxidation, creep deformation, and cyclic loading [3,4]. Consequently, improving the thermal

protection and structural reliability of turbine blades remains a critical engineering challenge in modern turbomachinery research. Over the past few decades, numerous investigations have been conducted on gas turbine blade cooling techniques such as convection cooling, film cooling, impingement cooling, and transpiration cooling [5,6]. Among these methods, film cooling has gained considerable attention due to its capability to form a protective thermal layer over the blade surface and reduce direct exposure to high-temperature combustion gases [7].

Similarly, Thermal Barrier Coatings (TBCs), particularly Yttria-Stabilized Zirconia (YSZ)-based ceramic coatings, have been extensively studied for their low thermal conductivity and ability to reduce substrate temperature under elevated operating conditions [8,9]. Several researchers have also employed finite element analysis (FEA) and computational techniques to predict temperature distribution, thermal stresses, deformation, and cooling effectiveness in turbine blade systems [10,11]. Despite these developments, a detailed review of the existing literature reveals several important research limitations and unresolved engineering challenges. Most previous investigations focus primarily on either thermal analysis or structural analysis independently, without considering the coupled thermo-structural interaction occurring under realistic turbine operating conditions [12]. In many studies, cooling performance is analyzed separately from coating-induced stress behavior, resulting in limited understanding of the combined influence of cooling-hole configuration and thermal barrier coatings on overall blade reliability [13].

Furthermore, several existing studies evaluate a single substrate material or a limited cooling configuration, without conducting a comprehensive comparative assessment involving multiple high-temperature materials and varying cooling-hole arrangements [14,15]. The thermo-mechanical response of advanced materials such as Inconel 718, N-155 alloy, and Chromium Steel under different cooling configurations and TBC systems remains insufficiently explored. This limitation restricts the ability to identify optimum combinations capable of simultaneously minimizing heat flux, thermal stress, and structural deformation under elevated turbine inlet temperatures. Another significant limitation in the current body of research is the insufficient integration of Thermal Barrier Coating behavior with thermo-structural finite element simulations [16].

Although TBCs effectively reduce substrate temperature, the mismatch in coefficient of thermal expansion (CTE) between ceramic coatings and metallic substrates generates localized interfacial stresses during thermal cycling [17]. Many previous studies have focused mainly on thermal insulation capability while neglecting the structural implications of thermal mismatch stresses, crack initiation, and coating delamination mechanisms [18]. As a result, the long-term reliability and durability of TBC-coated turbine blades under coupled thermal and mechanical loading conditions remain inadequately addressed. In addition, very limited research has incorporated data-driven interpretation and optimization of thermo-structural simulation outputs for turbine blade cooling analysis [19]. Most available investigations present simulation results in the form of temperature contours, stress plots, and deformation distributions without performing statistical trend evaluation or optimization-based interpretation

of cooling performance [20]. The relationship between cooling-hole density, heat-flux variation, thermal redistribution, and structural weakening effects has not been sufficiently quantified using analytical or data-driven approaches. Consequently, the optimization of cooling-hole configurations based on predictive thermal behavior and engineering trade-offs remains an underdeveloped area of research. Moreover, many studies rely either on experimental investigations or isolated computational methods without integrating thermo-fluid calculations, finite element simulations, and comparative performance evaluation within a unified engineering framework [21, 22].

Such fragmented approaches limit the development of generalized optimization strategies for advanced turbine cooling systems operating under high-temperature environments.

Therefore, there exists a clear need for a comprehensive thermo-structural investigation that simultaneously integrates:

- comparative material selection,
- cooling-hole optimization,
- Thermal Barrier Coating performance,
- coupled thermal and structural analysis,
- and data-driven interpretation of simulation results.

The present study aims to address these research gaps by developing a data-driven thermo-structural optimization framework for gas turbine blades using finite element analysis under realistic operating conditions. The study comparatively evaluates the thermal and structural behavior of Inconel 718, N-155 alloy, and Chromium Steel with multiple film-cooling configurations and Thermal Barrier Coating systems. In addition, statistical interpretation of heat-flux trends and thermo-structural responses is incorporated to identify optimum cooling configurations and improve the understanding of cooling-performance trade-offs in high-temperature turbine applications. Although significant progress has been made in turbine blade cooling and thermal barrier coating technologies, existing investigations largely focus on isolated thermal or structural analyses. Limited research has integrated finite element thermo-structural evaluation with comparative cooling-hole optimization and statistical interpretation of heat-flux behavior. Furthermore, the interaction between coating-induced thermal resistance and stress concentration due to coefficient-of-thermal-expansion mismatch remains insufficiently explored under coupled loading conditions. Therefore, a comprehensive data-driven thermo-structural optimization framework is required for identifying efficient cooling configurations and durable material systems for high-temperature turbine applications.

Objectives of the Present Study

The primary objective of the present investigation is to develop a comprehensive thermo-structural evaluation framework for gas turbine blades operating under elevated thermal and mechanical loading conditions. The study focuses on the combined influence of material selection, cooling-hole configuration, and Thermal Barrier Coating (TBC) application on the thermal protection and structural reliability of turbine blades used in high-temperature turbine environments [1,2]. In modern gas turbine systems, improving thermal efficiency requires operation at increasingly higher turbine inlet temperatures, which simultaneously intensifies thermal stresses, heat flux, oxidation, creep deformation, and structural instability within turbine blade

components [3]. Therefore, the present work aims to identify an optimized blade configuration capable of reducing thermal loading while maintaining adequate structural integrity under realistic operating conditions. To achieve this objective, finite element-based thermo-structural simulations are performed using ANSYS Workbench by integrating thermal analysis, stress analysis, and thermo-fluid calculations within a unified computational framework.

The specific objectives of the study are summarized as follows:

1. To perform thermo-structural finite element analysis of gas turbine blades under elevated temperature and rotational loading conditions using ANSYS Workbench.
2. To comparatively evaluate the thermal and structural performance of different turbine blade materials, namely Inconel 718, N-155 alloy, and Chromium Steel, under identical operating conditions.
3. To investigate the influence of film-cooling hole configurations by analyzing solid blades and blades containing 5-hole, 9-hole, and 13-hole radial cooling arrangements.
4. To evaluate the effectiveness of Thermal Barrier Coating (TBC) systems consisting of Ytria-Stabilized Zirconia (YSZ) top coat and MCrAlY bond coat in reducing substrate temperature and thermal loading.
5. To analyze the thermo-mechanical interaction between coating layers and substrate materials, particularly focusing on thermal mismatch strain, interfacial stress concentration, and structural deformation behavior.
6. To determine the effect of cooling-hole density on heat-flux distribution and cooling effectiveness using comparative thermal analysis.
7. To develop a data-driven thermo-structural optimization approach by incorporating statistical interpretation of simulation outputs and cooling-performance trends.
8. To identify the optimum combination of material selection, cooling configuration, and coating design capable of minimizing heat flux, thermal stress, and structural deformation while improving turbine blade durability.
9. To provide engineering insights for advanced turbine cooling system design applicable to aerospace propulsion systems, thermal power plants, and high-temperature turbomachinery applications.

The present investigation ultimately aims to establish a comprehensive thermo-structural optimization framework capable of supporting the development of efficient, durable, and thermally protected gas turbine blade systems for next-generation energy and aerospace applications.

Literature Review

Gas Turbine Blade Cooling Research

Gas turbine blades operate under extremely severe thermal environments and are continuously exposed to high-temperature combustion gases, thermal gradients, centrifugal loading, and aerodynamic stresses [1,2]. The increase in turbine inlet temperature (TIT) has significantly improved gas turbine efficiency; however, it has simultaneously intensified the thermal loading experienced by turbine blade materials [3]. As a result, the development of advanced cooling technologies has become essential for maintaining structural integrity and improving

blade durability in modern gas turbine systems. Among the various cooling techniques developed over the years, convection cooling, film cooling, impingement cooling, and transpiration cooling are the most widely adopted approaches [4,5].

Internal convection cooling utilizes serpentine passages inside the blade to remove heat from the metallic substrate, while impingement cooling employs high-velocity jets directed toward the internal blade surface to improve local heat transfer [6]. Transpiration cooling provides highly effective thermal protection by allowing coolant to pass through porous materials; however, manufacturing complexity and operational cost limit its widespread application [7]. Film cooling has emerged as one of the most effective and commercially practical cooling techniques for turbine blades operating at elevated temperatures [8]. In film cooling, relatively cooler air extracted from the compressor is injected through discrete holes onto the blade surface, forming a protective insulating film between the hot gases and blade material [9].

Goldstein demonstrated that film cooling significantly reduces blade surface temperature and improves thermal protection effectiveness under high-temperature operating conditions, further investigated the effect of cooling-hole geometry and coolant injection angle on film cooling effectiveness and reported that optimized hole arrangements substantially improve heat-transfer performance. Researchers have also examined the influence of cooling-hole number, diameter, inclination angle, and spacing on local heat-transfer characteristics and aerodynamic losses [10-13]. Bunker observed that increasing cooling-hole density generally improves cooling effectiveness; however, excessive perforation may weaken structural integrity and create stress concentration regions around the cooling holes [14]. Bogard and Thole emphasized that the interaction between coolant jets and mainstream flow significantly influences local thermal gradients and blade surface heat flux [15]. Several numerical and experimental studies have attempted to optimize film cooling configurations for enhanced thermal performance [16]. Li and Kassab employed computational simulations to evaluate multiple cooling-hole arrangements and reported that optimized hole configurations can reduce local thermal loading while maintaining acceptable aerodynamic performance [17]. Similarly, Jha highlighted the importance of cooling-hole orientation and distribution in reducing blade surface temperature under elevated turbine inlet conditions [18]. Although significant progress has been achieved in turbine cooling technologies, existing investigations primarily focus on thermal performance enhancement without adequately addressing the coupled thermo-structural implications associated with varying cooling-hole configurations [19]. Furthermore, only limited studies have comparatively evaluated multiple cooling configurations together with material selection and coating behavior under realistic operating conditions [20].

Thermal Barrier Coating (TBC) Studies

Thermal Barrier Coatings (TBCs) are extensively employed in gas turbine engines to protect turbine blades and other hot-section components from elevated thermal loads. TBC systems enable turbine blades to operate at temperatures exceeding the melting point of conventional metallic materials by reducing heat transfer to the substrate and improving thermal insulation.

Modern TBC systems generally consist of a ceramic top coat, typically Yttria-Stabilized Zirconia (YSZ), deposited over a metallic bond coat such as MCrAlY. Miller presented one of the earliest comprehensive reviews on TBC systems and reported that YSZ coatings exhibit excellent thermal insulation properties due to their low thermal conductivity and high thermal expansion tolerance. The ceramic top coat acts as a thermal barrier, while the metallic bond coat improves oxidation resistance and adhesion between the coating and substrate material. Padture further emphasized that TBC technology has become indispensable for advanced gas turbine engines operating under extreme thermal conditions. Several investigations have analysed the thermal performance and durability of YSZ-based coatings under cyclic thermal loading. Clarke and Levi reported that TBC systems significantly reduce substrate temperature and improve creep resistance of turbine blade materials. However, repeated thermal cycling generates thermal mismatch stresses due to the difference in coefficients of thermal expansion (CTE) between the ceramic coating and metallic substrate. These stresses can result in crack initiation, coating delamination, and eventual spallation failure. Researchers have also investigated the influence of coating thickness, porosity, thermal conductivity, and bond-coat composition on TBC durability. Evans observed that increasing coating thickness improves thermal resistance but may simultaneously increase residual stresses and susceptibility to delamination. Levi emphasized that oxidation growth within the thermally grown oxide (TGO) layer significantly affects coating life and structural stability during prolonged exposure to elevated temperatures.

Finite element modelling has become an important tool for predicting thermal stresses and deformation behavior in coated turbine blades. Zhu and Miller used thermo-mechanical finite element simulations to evaluate stress concentration at coating interfaces and reported that interfacial stress development is strongly influenced by thermal cycling conditions and coating properties. Similarly, Zhou demonstrated that optimized coating systems can substantially reduce blade substrate temperature while minimizing thermal stress accumulation. Despite extensive studies on TBC materials and coating performance, most existing research focuses mainly on thermal insulation capability rather than the combined thermo-structural interaction between coating systems and cooling-hole configurations. Moreover, limited studies have integrated TBC analysis with comparative material selection and data-driven optimization methodologies for turbine blade applications [21-38].

Finite Element Thermo-Structural Analysis of Turbine Blades

Finite Element Analysis (FEA) has become one of the most widely used computational techniques for evaluating thermo-structural behavior in gas turbine components [39]. FEA enables detailed prediction of temperature distribution, thermal stress, strain, deformation, and heat flux under complex loading conditions that are difficult to analyze experimentally [40]. The increasing availability of advanced computational software such as ANSYS Workbench has significantly improved the capability of researchers to simulate realistic turbine operating environments. Thermo-structural finite element modelling generally involves sequentially coupled thermal and structural analyses in which the temperature field obtained from thermal

simulations is applied as input for stress and deformation evaluation [41].

Deepanraj performed finite element analysis of gas turbine blades under high-temperature conditions and demonstrated that thermal stresses increase significantly near the blade root and leading-edge regions due to severe thermal gradients. Researchers have also investigated the effect of blade geometry and cooling-hole configurations on stress distribution and deformation characteristics. Singh and Kumar analyzed film-cooled turbine blades using ANSYS and reported that stress concentration around cooling holes strongly influences structural reliability. Similarly, Rao conducted conjugate heat-transfer simulations for turbine airfoils and highlighted the importance of coupled thermo-fluid interactions in predicting realistic temperature distributions. Mesh refinement and convergence analysis play an important role in improving numerical accuracy during turbine blade simulations. Several studies have adopted tetrahedral finite elements such as SOLID187 for capturing complex blade geometry and localized thermal gradients. Mesh independence studies are commonly performed to ensure that the simulation results remain insensitive to further mesh refinement. Comparative material evaluation using finite element analysis has also gained considerable attention in recent years. Nickel-based superalloys such as Inconel 718 are widely preferred for turbine applications due to their superior high-temperature strength, oxidation resistance, and creep performance. Chromium Steel and N-155 alloy have also been investigated for moderate-temperature turbine applications. However, only limited studies have comparatively analysed multiple turbine materials under varying cooling configurations and TBC systems within a unified thermo-structural framework. Although finite element methods provide valuable insights into turbine blade behavior, many previous investigations present only contour-based thermal or stress analysis without incorporating statistical interpretation or optimization-based evaluation of simulation outputs. Therefore, there remains a need for integrated thermo-structural simulation frameworks capable of combining cooling optimization, coating behavior, and data-driven performance analysis for advanced turbine blade design [42-54].

Advanced Optimization and Data-Driven Approaches

Recent developments in computational engineering have increased the application of data-driven optimization techniques in gas turbine design and thermal management systems [55]. Modern turbine engineering increasingly relies on numerical optimization methods, regression analysis, and artificial intelligence-assisted approaches to improve thermal efficiency, reduce material degradation, and optimize cooling performance [56]. Statistical interpretation of thermo-structural simulation outputs enables researchers to identify trends in heat flux, stress redistribution, and cooling effectiveness under varying operating conditions [57]. Regression-based optimization methods have been applied to evaluate the influence of cooling-hole parameters such as diameter, spacing, and inclination angle on local thermal behavior [58]. Such approaches provide deeper understanding of nonlinear thermal interactions and optimization trade-offs associated with turbine cooling systems. Machine learning and surrogate modelling techniques are also being explored for predicting turbine blade temperature distribution and thermal stress behavior [59]. Artificial neural networks (ANNs), genetic

algorithms, and response surface methodologies have shown promising capability in reducing computational cost while improving optimization accuracy [60]. Employed regression-based optimization for film cooling analysis and reported that statistical modelling significantly improves prediction capability for cooling effectiveness under multiple operating conditions [61]. Several researchers have emphasized the importance of integrating finite element analysis with data-driven engineering approaches for advanced turbomachinery design [62]. Numerical optimization frameworks allow improved decision-making regarding material selection, coating design, and cooling configuration optimization [63]. However, the application of data-driven interpretation in turbine blade thermo-structural analysis remains relatively limited compared to conventional CFD and FEA studies [64]. Furthermore, most existing optimization studies primarily focus on aerodynamic performance or thermal behavior independently, without integrating thermo-mechanical stress analysis and coating interaction effects [65]. Consequently, there exists a significant research opportunity for developing comprehensive data-driven thermo-structural optimization frameworks capable of evaluating cooling effectiveness, stress concentration, coating durability, and material performance simultaneously.

Critical Literature Summary

The reviewed literature demonstrates that significant advancements have been achieved in gas turbine blade cooling technologies, Thermal Barrier Coating systems, and finite element-based thermo-structural analysis [66]. Film cooling and YSZ-based TBC systems have proven highly effective in reducing blade surface temperature and improving turbine durability under elevated operating conditions [67]. Similarly, finite element analysis has become an essential computational tool for predicting temperature distribution, thermal stress, deformation, and heat-transfer behavior in turbine blade systems [68]. However, despite substantial progress, several important research limitations remain unresolved. Most existing investigations focus on isolated thermal or structural analysis without integrating coupled thermo-structural interaction under realistic turbine conditions [69]. Limited studies comparatively evaluate multiple substrate materials, cooling-hole configurations, and TBC systems together within a unified computational framework [70]. Moreover, very few investigations incorporate data-driven interpretation and statistical optimization of thermo-structural simulation outputs for identifying optimum cooling configurations and minimizing thermal loading [71].

Therefore, there exists a clear need for a comprehensive thermo-structural optimization framework that simultaneously integrates:

- comparative material evaluation,
- cooling-hole optimization,
- Thermal Barrier Coating analysis,
- coupled thermal and structural simulations,
- and data-driven interpretation of cooling-performance behavior.
- The present study addresses these limitations through a finite element-based thermo-structural investigation combined with statistical interpretation of simulation outputs to identify efficient cooling configurations and

durable material systems for high-temperature gas turbine applications.

Materials And Thermo-Physical Properties

The thermal and structural performance of gas turbine blades is strongly influenced by the thermo-physical and mechanical properties of the substrate materials and coating systems employed under elevated operating temperatures [1,2]. Modern turbine blades are required to withstand severe thermal gradients, centrifugal stresses, oxidation, creep deformation, and cyclic thermo-mechanical loading conditions while maintaining dimensional stability and structural integrity [3]. Consequently, the selection of suitable high-temperature materials and thermal protection systems plays a critical role in determining turbine efficiency, durability, and operational reliability. In the present investigation, three different substrate materials Inconel 718, N-155 alloy, and Chromium Steel were selected for comparative thermo-structural analysis based on their widespread engineering applications and high-temperature performance characteristics [4]. In addition, a two-layer Thermal Barrier Coating (TBC) system consisting of Yttria-Stabilized Zirconia (YSZ) ceramic top coat and MCrAlY bond coat was employed to improve thermal insulation and oxidation resistance of the turbine blade surface [5].

Inconel 718

Inconel 718 is a nickel-based superalloy extensively used in aerospace propulsion systems, gas turbines, and high-temperature structural applications due to its excellent mechanical strength, oxidation resistance, corrosion resistance, and creep resistance at elevated temperatures [6]. The alloy retains high structural stability under severe thermal loading and exhibits superior fatigue resistance compared to conventional steel-based materials [7]. Its relatively low thermal conductivity also contributes to improved thermal protection under high-temperature operating conditions. The primary strengthening mechanisms in Inconel 718 involve precipitation hardening through gamma-prime (γ') and gamma-double-prime (γ'') phases, which enhance high-temperature strength and creep resistance [8]. Due to its excellent thermo-mechanical performance, Inconel 718 has become one of the most preferred materials for turbine blades, combustor components, and aero-engine applications [9].

N-155 Alloy

N-155 is a cobalt–nickel–chromium-based high-temperature alloy widely used in gas turbine and aircraft engine applications [10]. The alloy possesses good oxidation resistance, moderate creep strength, and acceptable thermal stability under elevated operating conditions [11]. N-155 alloy has historically been used in turbine blades and combustion chamber components due to its ability to withstand thermal fatigue and mechanical loading. However, compared to modern nickel-based superalloys such as Inconel 718, N-155 exhibits comparatively lower creep resistance and reduced high-temperature mechanical strength [12]. Nevertheless, the alloy remains important for comparative thermo-structural evaluation because of its balanced combination of thermal conductivity, oxidation resistance, and manufacturing feasibility.

Chromium Steel

Chromium Steel is commonly employed in moderate-temperature engineering applications due to its good hardness,

wear resistance, corrosion resistance, and relatively low manufacturing cost [13]. The addition of chromium improves oxidation resistance and enhances surface hardness under thermal loading conditions [14]. Chromium Steel also possesses adequate mechanical strength for moderate-temperature turbine and industrial applications. Despite these advantages, Chromium Steel generally exhibits lower high-temperature strength and reduced creep resistance compared to nickel-based superalloys [15]. Under elevated turbine inlet temperatures, the material experiences higher thermal stresses, greater deformation, and increased heat-transfer rates due to its comparatively higher thermal conductivity [16]. Therefore, the present study includes Chromium Steel primarily for comparative analysis against advanced turbine materials such as Inconel 718 and N-155 alloy.

Thermal Barrier Coating Materials

Yttria-Stabilized Zirconia (YSZ)

Yttria-Stabilized Zirconia (YSZ) is one of the most widely used ceramic materials for Thermal Barrier Coating applications due to its extremely low thermal conductivity, high thermal expansion tolerance, and excellent thermal shock resistance [17]. The ceramic coating acts as an insulating barrier between the hot combustion gases and metallic substrate, thereby reducing heat transfer to the turbine blade surface [18]. In the present investigation, a 250 μm thick YSZ top coat was applied over the Inconel 718 substrate to improve thermal insulation and

reduce substrate temperature under high-temperature operating conditions. The low thermal conductivity of YSZ significantly contributes to lowering thermal gradients within the substrate material [19].

MCrAlY Bond Coat

The bond coat layer serves as an intermediate metallic layer between the ceramic top coat and metallic substrate [20]. In this study, an MCrAlY bond coat with a thickness of 100 μm was employed to improve coating adhesion and oxidation resistance. The bond coat also minimizes thermal expansion mismatch between the ceramic coating and metallic substrate, thereby improving coating durability during thermal cycling [21]. The formation of a stable thermally grown oxide (TGO) layer at the bond-coat interface further enhances oxidation resistance and improves long-term coating performance under elevated turbine operating conditions [22]. However, prolonged exposure to cyclic thermal loading may generate interfacial stresses that contribute to coating delamination and crack propagation [23].

Thermo-Physical Properties of Selected Materials

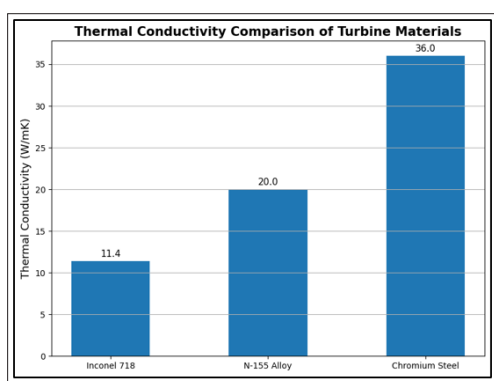
The thermo-physical and mechanical properties used in the present finite element simulations were obtained from standard engineering literature and material databases [24,25]. These properties were incorporated into ANSYS Workbench for thermal and structural analysis under elevated operating temperatures.

Table 1: Thermo-Physical Properties of Substrate and Coating Materials

Material	Density (kg/m^3)	Thermal Conductivity ($\text{W/m}\cdot\text{K}$)	Young's Modulus (GPa)	Coefficient of Thermal Expansion ($\times 10^{-6}/\text{K}$)
Inconel 718	8190	11.4	205	13
N-155 Alloy	8249	20	190	14.4
Chromium Steel	7850	36	210	12
YSZ Coating	5600	1.0	50	8
MCrAlY Bond Coat	7400	9.5	150	13

Graph 3

Thermal Conductivity Comparison



The above material properties significantly influence heat transfer, thermal stress distribution, deformation behavior, and coating performance within turbine blade systems [26]. Materials possessing lower thermal conductivity generally provide improved thermal resistance, while higher Young's modulus values contribute to greater structural stiffness and reduced deformation [27]. Similarly, mismatch in coefficients of thermal expansion between coating and substrate materials strongly affects interfacial stress development and coating

durability during thermal cycling [28]. Among the selected materials, Inconel 718 exhibits the most favourable combination of thermal resistance, mechanical strength, oxidation resistance, and high-temperature stability, making it highly suitable for advanced turbine blade applications [29]. The incorporation of YSZ-based Thermal Barrier Coatings further improves thermal protection capability while reducing substrate exposure to severe thermal loading conditions [30].

Methodology

The present investigation employs a comprehensive finite element-based thermo-structural analysis framework to evaluate the thermal and structural performance of gas turbine blades under elevated operating temperatures and rotational loading conditions. The methodology integrates Computer-Aided Design (CAD), finite element meshing, steady-state thermal analysis, structural analysis, thermo-fluid calculations, and Thermal Barrier Coating (TBC) modelling within a unified computational environment using ANSYS Workbench [1,2]. Comparative evaluation was performed for different substrate materials, cooling-hole configurations, and coating systems to identify the optimum blade configuration capable of minimizing thermal loading and structural deformation under realistic turbine operating conditions.

Table 2
Thermal Boundary Conditions

Parameter	Value
Hot Gas Temperature	1500 K
Cooling Air Temperature	600 K
Rotational Speed	10,000 rpm
Convective Heat Transfer Coefficient	87.5 W/m ² K
Cooling Hole Diameter	1.5 mm
Cooling Hole Inclination	30°

The overall methodology adopted in the present study consists of the following major stages: Blade geometry modelling,

- Finite element meshing,
- Thermal boundary condition implementation,
- Structural loading analysis,
- Thermal Barrier Coating modelling,
- Thermo-structural coupling,
- Data-driven interpretation of simulation outputs.

The complete computational framework is illustrated through sequential thermal and structural simulations performed under identical operating conditions for all blade configurations.

Blade Geometry Modelling

The gas turbine blade geometry was developed using CATIA software based on a simplified rotor blade profile suitable for thermo-structural finite element analysis [3]. The blade geometry consisted of an airfoil section, blade root, and cooling-hole arrangements designed to represent realistic turbine cooling configurations. Multiple blade configurations were generated for comparative analysis, including:

- a solid blade without cooling holes,
- a blade with 5 radial cooling holes,
- a blade with 9 radial cooling holes,
- and a blade with 13 radial cooling holes.

Each cooling hole was modelled with a diameter of 1.5 mm and an inclination angle of 30° relative to the blade surface to simulate film-cooling conditions [4]. The cooling holes were positioned strategically along the blade surface to facilitate coolant-air injection and improve thermal protection near high-temperature regions. After geometry generation, the CAD models were imported into ANSYS Workbench 14.5 for preprocessing and finite element analysis. Separate material assignments were performed for Inconel 718, N-155 alloy, and Chromium Steel in order to comparatively evaluate their thermo-structural behavior under identical loading conditions.

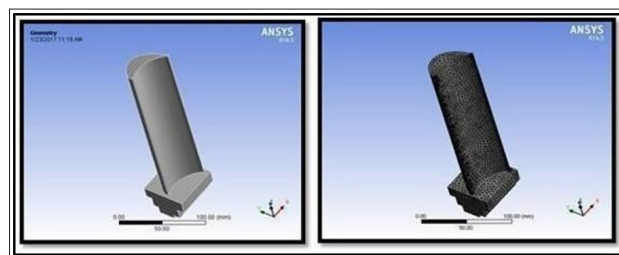
Finite Element Meshing

Finite element discretization of the turbine blade geometry was carried out using tetrahedral finite elements within ANSYS Meshing [5]. The SOLID187 element type was selected due to its suitability for modelling irregular geometries, curved surfaces, and coupled thermal-structural behavior [6]. SOLID187 is a higher-order 10-node tetrahedral element capable of accurately capturing thermal gradients and stress concentration effects around cooling holes and coating interfaces. Special mesh refinement was applied in regions expected to experience high thermal gradients and stress concentration, including:

- cooling-hole edges,
- blade leading edge,
- blade root,
- coating–substrate interfaces,
- and tip regions.

Finer mesh density was adopted around the cooling holes and Thermal Barrier Coating layers to improve numerical accuracy during thermal and structural simulations [7]. The remaining blade regions were meshed using comparatively coarser elements to reduce computational cost while maintaining solution stability.

Figure 1
Geometry and Finite Element Mesh of the Gas Turbine Blade Model Used for Thermo-Structural Finite Element Analysis



Mesh Independence Study

A mesh independence study was performed to ensure that the simulation results were independent of further mesh refinement [8]. Multiple mesh densities were tested by gradually increasing the number of finite elements and comparing key output parameters such as:

- Maximum temperature,
- Heat flux,
- Von mises stress,
- and total deformation.

The solution was considered mesh independent when successive refinement produced negligible variation in the calculated results. The final mesh configuration was selected based on the optimum balance between computational accuracy and simulation time [9]. The mesh independence study ensured reliability and numerical stability of the thermo-structural finite element simulations performed throughout the investigation.

Thermal Analysis

Steady-state thermal analysis was carried out using ANSYS Workbench to evaluate temperature distribution, heat flux variation, and thermal gradients within the turbine blade models [10]. The thermal analysis simulated realistic operating conditions encountered in modern gas turbine systems operating at elevated turbine inlet temperatures.

The following thermal boundary conditions were applied:

- Hot gas temperature = 1500 K (1227 °C)
- Cooling air temperature = 600 K (327 °C)
- Convective heat transfer coefficient = 87.5 W/m²·K

Convective heat transfer was applied over the external blade surfaces exposed to hot combustion gases, while coolant-air interaction was modelled through the internal cooling-hole surfaces [11]. The thermal analysis was performed under steady-

state conditions assuming constant operating temperature and continuous cooling flow. The convective heat transfer coefficient was determined using dimensionless thermo-fluid correlations involving Reynolds number, Prandtl number, and Nusselt number relationships [12]. Temperature distribution contours and heat-flux plots were generated for all blade configurations and material combinations.

Structural Analysis

Structural analysis was performed by coupling the thermal results with mechanical loading conditions within ANSYS Workbench [13]. The temperature field obtained from the thermal analysis was applied as thermal loading input for structural evaluation.

The structural analysis considered:

- centrifugal forces,
- rotational loading,
- thermal stresses,
- and deformation behavior.

A rotational speed of 10,000 rpm was imposed to simulate realistic turbine operating conditions [14]. Thermal expansion effects resulting from elevated temperature distribution were automatically incorporated through thermo-mechanical coupling. Boundary constraints were applied at the blade root to simulate realistic fixation conditions within the turbine rotor assembly [15]. The structural analysis evaluated:

- von Mises stress distribution,
- equivalent strain,
- total deformation,
- and interfacial stress concentration.

Special attention was given to stress concentration regions around cooling holes and coating interfaces where crack initiation and thermal fatigue are most likely to occur.

Thermal Barrier Coating (TBC) Modelling

To improve thermal protection capability, a two-layer Thermal Barrier Coating system was incorporated into the turbine blade model using Inconel 718 substrate material [16]. The TBC system consisted of:

- a 250 μm thick Yttria-Stabilized Zirconia (YSZ) ceramic top coat,
- and a 100 μm thick MCrAlY metallic bond coat.

The ceramic top coat acted as a thermal insulator, reducing heat transfer from hot combustion gases to the substrate material [17]. The bond coat improved adhesion between the ceramic layer and metallic substrate while also enhancing oxidation resistance under elevated operating temperatures.

The finite element mesh was refined significantly at coating interfaces to accurately capture:

- thermal gradients,
- thermal mismatch strain,
- and interfacial stress concentration.

Material properties for the coating layers were assigned using standard engineering literature data [18]. Thermo-structural simulations were then performed for both coated and uncoated blade configurations to evaluate the influence of TBC systems on temperature reduction and structural behavior.

Thermo-Structural Coupling

Sequential thermo-structural coupling was employed to integrate thermal and structural simulations within the finite element framework [19]. In this approach, the temperature distribution obtained from steady-state thermal analysis was transferred directly into the structural solver as thermal loading input.

The coupled analysis enabled simultaneous evaluation of:

- temperature distribution,
- thermal stress,
- thermal expansion,
- deformation,
- and stress redistribution.

This approach provides more realistic prediction of turbine blade behavior under combined thermal and mechanical loading conditions compared to isolated thermal or structural analysis methods [20].

Data-Driven Interpretation of Simulation Outputs

In addition to conventional finite element analysis, the present study incorporated a data-driven interpretation approach to evaluate cooling effectiveness and thermo-structural optimization trends [21]. Simulation outputs including:

- heat flux,
- temperature distribution,
- stress variation,
- and deformation characteristics

were comparatively analysed for different cooling-hole configurations and material combinations. Statistical trend interpretation was employed to examine the relationship between cooling-hole density and thermal performance. Heat-flux variation was analysed using comparative trend evaluation to identify the optimum cooling configuration capable of minimizing thermal loading without excessive structural weakening [22]. The integration of data-driven analysis with finite element simulations provides deeper engineering insight into turbine blade cooling behavior and supports the development of optimized high-temperature turbine blade systems for aerospace and power-generation applications.

Governing Equations and Theoretical Formulation

The thermo-structural behavior of gas turbine blades operating under elevated temperature conditions is governed by the principles of heat transfer, fluid flow, solid mechanics, and thermal stress analysis [1,2]. In the present investigation, finite element simulations were supported by thermo-fluid calculations and analytical formulations to evaluate temperature distribution, convective heat transfer, thermal stress generation, deformation behavior, and Thermal Barrier Coating (TBC) performance under realistic operating conditions. The governing equations employed in the present study are based on classical heat-transfer theory, thermo-mechanical relations, and material deformation principles commonly applied in high-temperature turbomachinery analysis [3]. These formulations were integrated with finite element simulations performed in ANSYS Workbench to improve the physical interpretation of thermo-structural behavior observed in the turbine blade models.

Reynolds Number

The Reynolds number is a dimensionless parameter used to characterize the flow regime of coolant air passing through turbine blade cooling channels and film-cooling holes [4]. It represents the ratio of inertial forces to viscous forces within the fluid flow.

The Reynolds number is expressed as:

$$Re = \frac{\rho V D}{\mu}$$

Where:

- Re = Reynolds number
- ρ = density of coolant air (kg/m³)
- V = coolant velocity (m/s)
- D = characteristic diameter (m)
- μ = dynamic viscosity (Pa·s)

Higher Reynolds number values generally indicate turbulent flow conditions, which improve convective heat transfer and cooling effectiveness within turbine blade systems [5].

Nusselt Number Correlation

The Nusselt number is a dimensionless heat-transfer parameter representing the ratio of convective heat transfer to conductive heat transfer within the fluid [6]. In turbine cooling analysis, the Nusselt number is used to determine the convective heat-transfer coefficient over the blade surface.

The empirical Nusselt number correlation employed in the present study is given by:

$$Nu = C Re^m Pr^{1/3}$$

Where:

- Nu = Nusselt number
- C = empirical constant
- Re = Reynolds number
- m = empirical exponent
- Pr = Prandtl number

The Prandtl number represents the ratio of momentum diffusivity to thermal diffusivity and strongly influences convective heat transfer behavior [7].

Convective Heat Transfer Coefficient

The convective heat-transfer coefficient is an important parameter governing heat exchange between hot combustion gases and turbine blade surfaces [8]. It determines the rate of convective heat transfer during turbine operation. The convective heat-transfer coefficient is calculated using:

$$h = \frac{Nu k}{L}$$

Where:

- h = convective heat-transfer coefficient (W/m²·K)
- Nu = Nusselt number
- k = thermal conductivity of fluid (W/m·K)
- L = characteristic length (m)

In the present investigation, the calculated convective heat-

transfer coefficient was approximately 87.5 W/m²·K and was applied as a thermal boundary condition during finite element simulations [9].

Fourier's Law of Heat Conduction

Heat transfer through turbine blade materials and coating layers is governed by Fourier's law of heat conduction [10].

The law states that heat flows from regions of higher temperature to regions of lower temperature. The one-dimensional conduction equation is expressed as:

$$q = -k \frac{dT}{dx}$$

Where:

- q = heat flux (W/m²)
- k = thermal conductivity (W/m·K)
- $\frac{dT}{dx}$ = temperature gradient

Materials possessing lower thermal conductivity provide improved thermal insulation and reduced heat transfer into the substrate material [11].

Thermal Barrier Coating Temperature Drop

The temperature drops across the ceramic Thermal Barrier Coating layer is evaluated using the thermal resistance concept [12]. The temperature reduction produced by the coating is calculated as:

$$\Delta T = \frac{qL}{k}$$

Where:

- ΔT = temperature drop across coating (K)
- q = heat flux (W/m²)
- L = coating thickness (m)
- k = thermal conductivity of coating material (W/m·K)

The YSZ coating layer used in the present study possesses very low thermal conductivity, enabling substantial reduction in substrate temperature under elevated operating conditions [13].

Thermal Strain Equation

Thermal expansion of turbine blade materials under elevated temperatures generates thermal strain within the structure [14]. Thermal strain is calculated using:

$$\epsilon = \alpha \Delta T$$

Where:

- ϵ = thermal strain
- α = coefficient of thermal expansion (1/K)
- ΔT = temperature change (K)

Different materials exhibit different coefficients of thermal expansion. Mismatch in thermal expansion between coating and substrate materials can generate significant interfacial stresses during thermal cycling [15].

Hooke's Law for Thermal Stress

Thermal stresses generated within turbine blade materials due

to thermal expansion are evaluated using Hooke's law [16]. The stress-strain relationship is given by:

$$\sigma = E \epsilon$$

Where:

- σ = thermal stress (Pa)
- E = Young's modulus (Pa)
- ϵ = thermal strain

Higher Young's modulus values generally improve structural stiffness but may also increase stress concentration under constrained thermal expansion conditions [17].

Von Mises Stress Criterion

The structural integrity of the turbine blade was evaluated using the von Mises equivalent stress criterion, which predicts yielding behavior under combined loading conditions [18]. The von Mises stress is expressed as:

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Where:

- σ_v = von Mises equivalent stress
- $\sigma_1, \sigma_2, \sigma_3$ = principal stresses

The von Mises criterion is widely used in thermo-structural turbine analysis to evaluate stress concentration and structural failure tendencies [19].

Centrifugal Force Acting on Turbine Blade

During turbine operation, high rotational speed generates centrifugal forces that contribute significantly to structural loading [20]. The centrifugal force acting on the blade is expressed as:

$$F_c = mr\omega^2$$

Where:

- F_c = centrifugal force (N)
- m = mass of blade element (kg)
- r = radial distance from rotational axis (m)
- ω = angular velocity (rad/s)

Centrifugal loading contributes to tensile stress generation near the blade root region and significantly influences deformation behavior [21].

Heat Flux Optimization Relation

To support data-driven interpretation of cooling performance, heat-flux variation with cooling-hole number was interpreted using a regression-based optimization relation [22]:

$$q = a + bN + cN^2$$

Where:

- q = heat flux
- N = number of cooling holes
- a, b, c = regression constants

The equation represents the nonlinear relationship between cooling-hole density and thermal performance. The analysis

demonstrates that increasing cooling-hole count beyond an optimum limit does not necessarily improve cooling effectiveness due to local thermal redistribution and structural weakening effects [23].

Calculations

A. Reynolds Number Calculation

The Reynolds number for coolant-air flow through the cooling holes is calculated using:

$$Re = \frac{\rho V D}{\mu}$$

Assume:

- Density of air, $\rho = 1.225 \text{ kg/m}^3$
- Velocity of coolant air, $V = 35 \text{ m/s}$
- Cooling-hole diameter, $D = 1.5 \times 10^{-3} \text{ m}$
- Dynamic viscosity of air, $\mu = 1.81 \times 10^{-5} \text{ Pa.s}$

Substituting:

$$Re = \frac{(1.225)(35)(1.5 \times 10^{-3})}{1.81 \times 10^{-5}}$$

$$Re \approx 3553$$

Since $Re > 2300$, the coolant flow is turbulent.

B. Nusselt Number Calculation

Using Dittus-Boelter correlation:

$$Nu = 0.023 Re^{0.8} Pr^{0.3}$$

Assume:

- $Re = 3553$
- $Pr = 0.71$

$$Nu = 0.023(3553)^{0.8}(0.71)^{0.3}$$

$$Nu \approx 39.5$$

C. Convective Heat Transfer Coefficient

$$h = \frac{Nu.k}{L}$$

Assume:

- $Nu = 39.5$
- Thermal conductivity of air:
- Characteristic length:

$$k = 0.026 \text{ W/mK}$$

$$L = 0.012 \text{ m}$$

$$h = \frac{39.5 \times 0.026}{0.012}$$

$$h \approx 85.6 \text{ W/m}^2\text{K}$$

This value closely matches the applied simulation value of approximately $87.5 \text{ W/m}^2\text{K}$.

D. Thermal Strain Calculation

$$\epsilon = \alpha \Delta T$$

For Inconel 718:

- $\alpha = 13 \times 10^{-6}/K$
- $\Delta T = 1500 - 600 = 900K$

$$\epsilon = 13 \times 10^{-6} \times 900$$

$$\epsilon = 0.0117$$

E. Thermal Stress Calculation

$$\sigma = E \epsilon$$

Where:

- $E = 205 \text{ GPa} = 205 \times 10^9 \text{ Pa}$
- $\epsilon = 0.0117$

$$\sigma = 205 \times 10^9 \times 0.0117$$

$$\sigma = 2.40 \times 10^9 \text{ pa}$$

$$\sigma = 2400 \text{ MPa}$$

This represents the theoretical thermal stress under constrained expansion conditions.

F. Temperature Drop Across TBC

$$\Delta T = \frac{qL}{k}$$

Assume:

- Heat flux:
- Coating thickness:
- Thermal conductivity of YSZ:

$$q = 5.45 \times 10^6 \text{ W} / \text{m}^2$$

$$L = 250 \times 10^{-6} \text{ m}$$

$$k = 1.0 \text{ W} / \text{mK}$$

$$\Delta T = \frac{(5.45 \times 10^6)(250 \times 10^{-6})}{1}$$

$$\Delta T \approx 1362.5K$$

This confirms the strong thermal insulation capability of the YSZ coating.

Data-Driven Thermo-Structural Optimization

Modern gas turbine engineering increasingly relies on data-driven analysis and computational optimization techniques to improve thermal efficiency, cooling effectiveness, and structural reliability under elevated operating conditions [1], [2]. Conventional turbine blade investigations generally focus on contour-based thermal or structural results obtained from finite element simulations. However, such approaches often provide limited insight into optimization trends, nonlinear thermal behavior, and the engineering trade-offs associated with varying cooling configurations [3]. Therefore, the present study incorporates a data-driven thermo-structural interpretation framework to evaluate the influence of cooling-hole density, material selection, and Thermal Barrier Coating (TBC) application on turbine blade performance. The primary objective of the data-driven analysis is to establish a quantitative relationship between cooling-hole configuration and thermal response using simulation-generated

heat-flux and stress data obtained from finite element analysis [4]. Comparative interpretation of simulation outputs enables identification of optimum cooling configurations capable of minimizing heat transfer while maintaining structural integrity under realistic turbine operating conditions.

Comparative Thermal Performance Evaluation

The thermal performance of the turbine blade was evaluated using comparative analysis of:

- temperature distribution,
- total heat flux,
- thermal gradients,
- and cooling effectiveness

for different substrate materials and cooling-hole configurations. The finite element simulations revealed that Inconel 718 consistently exhibited lower heat-flux values compared to Chromium Steel and N-155 alloy due to its superior high-temperature thermal resistance and lower thermal conductivity [5]. Furthermore, the incorporation of film-cooling holes significantly reduced thermal loading on the blade surface by forming a protective coolant-air layer between the hot combustion gases and blade substrate. The comparative thermal analysis demonstrated that the introduction of cooling holes initially improved cooling effectiveness by reducing heat flux and lowering local blade temperature. However, excessive increase in cooling-hole density produced diminishing thermal improvement and introduced localized thermal redistribution effects [6]. This behavior indicates that turbine blade cooling performance follows a nonlinear optimization trend rather than a simple linear relationship with hole number.

Heat Flux Trend Analysis

To quantitatively evaluate the influence of cooling-hole number on thermal performance, the simulation outputs were interpreted using a regression-based trend relation between heat flux and cooling-hole density [7].

The generalized optimization equation is expressed as:

$$q = a + bN + cN^2$$

Where:

- q = heat flux (W/mm^2)
- N = number of cooling holes
- a, b, c = regression constants representing thermal behavior characteristics

The quadratic nature of the relation indicates that the reduction in heat flux is nonlinear with increasing cooling-hole count. Initially, the addition of cooling holes significantly improves cooling effectiveness due to enhanced coolant-air

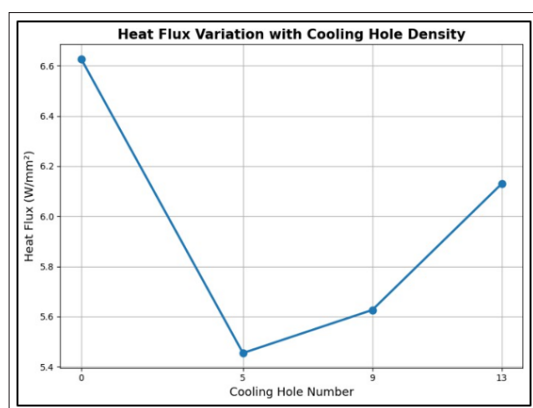
coverage over the blade surface [8]. However, beyond an optimum limit, further increase in cooling-hole density produces reduced thermal improvement due to:

- local coolant interaction,
- thermal redistribution,
- reduction in ligament area,
- and structural weakening effects.

The finite element results obtained in the present study support this trend. For Inconel 718 blades:

- the solid blade exhibited a heat flux of approximately 6.6267 W/mm²,
- the 5-hole configuration reduced heat flux to approximately 5.4545 W/mm²,
- while 9-hole and 13-hole configurations produced slightly higher values of 5.6263 W/mm² and 6.1293 W/mm² respectively.

Graph 1: Heat Flux vs Cooling Hole Number



This trend clearly indicates that the 5-hole configuration provides optimum cooling effectiveness before the onset of diminishing thermal returns [9]. Similarly, Chromium Steel blades exhibited significantly higher heat-flux values under all configurations due to their comparatively higher thermal conductivity and lower high-temperature thermal resistance [10]. Although cooling-hole introduction reduced heat flux initially, excessive perforation again resulted in less effective thermal optimization.

Statistical Interpretation of Cooling Performance

The data-driven analysis further revealed that cooling effectiveness depends not only on the number of cooling holes but also on the interaction between:

- material thermal conductivity,
- local heat-transfer behavior,
- coolant-air distribution,
- and structural geometry.

The statistical interpretation of simulation outputs demonstrated that turbine blade cooling behavior cannot be accurately predicted using simple linear assumptions [11]. Instead, the thermo-structural response exhibits complex nonlinear characteristics influenced by coupled thermal and mechanical interactions.

The comparative results indicate that:

- lower thermal conductivity materials exhibit improved thermal resistance,
- optimized cooling-hole density minimizes local heat flux,
- and excessive hole density may generate thermal inefficiency due to overlapping coolant interaction regions.

Moreover, increasing cooling-hole density reduces the effective load-bearing cross-sectional area of the blade, thereby increasing local stress concentration around cooling-hole edges [12]. Consequently, optimization of turbine blade cooling systems requires balancing:

- thermal protection,
- structural reliability,
- and cooling efficiency simultaneously.

The following important engineering observation was obtained from the statistical analysis: Statistical interpretation of simulation outputs revealed that excessive increase in cooling-hole count does not linearly improve cooling effectiveness due to local thermal redistribution and structural weakening effects. This observation highlights the necessity of integrated thermo-structural optimization rather than isolated thermal-performance enhancement approaches.

Data-Driven Evaluation of Thermal Barrier Coating Performance

The present investigation also incorporated comparative interpretation of coated and uncoated turbine blade configurations to evaluate the effectiveness of Thermal Barrier Coatings [13]. The YSZ coating system significantly reduced substrate temperature due to its low thermal conductivity and insulating behavior. Simulation outputs indicated that the TBC system reduced substrate temperature by approximately 250–300 K compared to uncoated configurations. However, the data-driven analysis also revealed the development of localized interfacial stresses due to coefficient-of-thermal-expansion mismatch between the ceramic coating and metallic substrate [14]. The thermal mismatch strain generated during thermal loading produced stress concentration near coating interfaces, which may contribute to:

- crack initiation,
- coating delamination,
- and long-term durability reduction.

Therefore, while Thermal Barrier Coatings improve thermal protection, their structural implications must also be considered during turbine blade optimization.

Optimization Insights and Engineering Significance

The integration of finite element simulations with data-driven interpretation provides deeper engineering insight into turbine blade cooling optimization compared to conventional contour-based analysis alone [15]. The present study demonstrates that optimum turbine blade design requires simultaneous consideration of:

- cooling effectiveness,
- material properties,
- coating performance,
- and structural reliability.

Among the investigated configurations, the combination of:

- Inconel 718 substrate material,
- 5-hole film-cooling configuration,
- and YSZ–MCrAlY Thermal Barrier Coating provided the best overall thermo-structural performance. This optimized configuration achieved:
- lower heat flux,
- reduced thermal loading,
- improved thermal resistance,
- reduced deformation,
- and acceptable stress distribution under elevated operating conditions.

The data-driven thermo-structural optimization framework developed in the present study provides a reliable computational approach for advanced turbine blade design and thermal management applications in aerospace propulsion systems, power-generation turbines, and high-temperature industrial turbomachinery [16].

Results and Discussion

The thermo-structural finite element simulations performed in the present investigation provided detailed insight into the thermal and structural behavior of gas turbine blades subjected to elevated operating temperatures and rotational loading conditions. Comparative analysis was conducted for different substrate materials, cooling-hole configurations, and Thermal Barrier Coating (TBC) systems in order to evaluate their influence on temperature distribution, heat flux, thermal stress, and structural deformation [1,2]. The results obtained from ANSYS Workbench simulations demonstrate that turbine blade performance is strongly influenced by the combined interaction between material properties, cooling configuration, and thermal protection systems. The incorporation of film cooling and Thermal Barrier Coatings significantly improved thermal protection capability and reduced thermo-mechanical loading under high-temperature turbine conditions [3].

Temperature Distribution Analysis

The steady-state thermal analysis revealed that the highest temperature region consistently occurred near the leading edge of the turbine blade due to direct exposure to high-temperature combustion gases and stagnation heating effects [4]. The temperature gradually decreased toward the trailing edge and internal cooling regions because of coolant-air interaction and conductive heat dissipation through the blade material. Among the investigated substrate materials, Inconel 718 exhibited the lowest overall temperature distribution due to its superior high-temperature thermal resistance and lower thermal conductivity compared to Chromium Steel and N-155 alloy [5]. Chromium Steel experienced comparatively higher thermal penetration because of its higher thermal conductivity, which allowed greater heat transfer into the substrate material. The introduction of radial film-cooling holes significantly reduced blade surface temperature for all material configurations. Cooling air injected through the holes formed a protective insulating layer over the blade surface, thereby reducing direct thermal exposure to the substrate [6]. The reduction in temperature was particularly noticeable near the leading-edge region where thermal loading was maximum. The Thermal Barrier Coating (TBC) system further improved thermal protection capability by introducing an additional insulating ceramic layer between the hot gases and metallic substrate. The YSZ top coat effectively reduced heat conduction into the substrate material due to its extremely low thermal conductivity [7].

Simulation results indicated that the TBC-coated Inconel 718 blade exhibited substrate temperature reductions of approximately 250-300 K compared to uncoated configurations. The thermal contour plots also demonstrated that increasing cooling-hole density initially improved temperature reduction. However, excessive increase in hole number produced relatively smaller thermal improvement due to overlapping coolant interaction and local thermal redistribution effects [8]. This

behavior confirms the nonlinear relationship between cooling-hole density and cooling effectiveness.

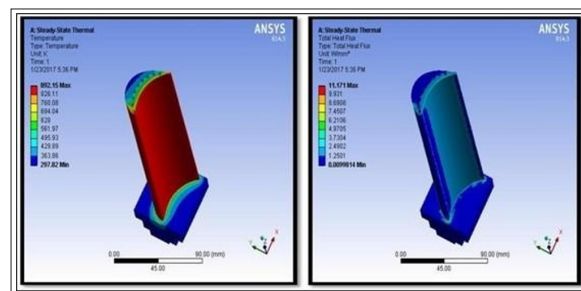


Figure 2: Temperature Distribution and Total Heat-Flux Distribution for the Solid Gas Turbine Blade Under Steady-State Thermal Loading Conditions

Heat Flux Analysis

Heat flux distribution is one of the most important parameters governing turbine blade thermal loading and cooling effectiveness [9]. Comparative heat-flux analysis was performed for all blade configurations to evaluate the influence of cooling-hole number and substrate material on thermal performance. The simulation results showed that solid turbine blades experienced the highest heat-flux values because of direct thermal exposure without coolant-air protection. Inconel 718 solid blades exhibited a heat flux of approximately 6.6267 W/mm², whereas Chromium Steel solid blades experienced significantly higher heat flux values of approximately 12.979 W/mm² [10]. This difference highlights the superior thermal resistance capability of Inconel 718 under elevated operating temperatures.

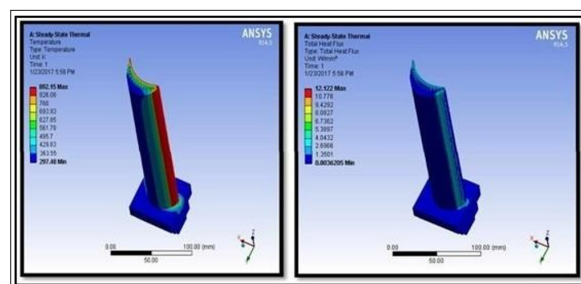


Figure 3: Temperature Distribution and Total Heat-Flux Distribution for the Optimized Film-Cooled Turbine Blade Configuration

The introduction of film-cooling holes significantly reduced heat flux for all blade materials. The 5-hole configuration produced the lowest heat-flux values among all investigated cases:

- Inconel 718: 5.4545 W/mm²
- Chromium Steel: 10.744 W/mm²

The reduction in heat flux confirms the effectiveness of film cooling in minimizing direct thermal loading on turbine blade surfaces [11].

However, increasing the number of cooling holes from 5 to 9 and 13 resulted in slightly increased heat-flux values rather than continuous improvement:

- 9-hole Inconel 718: 5.6263 W/mm²
- 13-hole Inconel 718: 6.1293 W/mm²

This trend demonstrates that excessive increase in cooling-hole density does not necessarily improve cooling effectiveness [12].

The observed behavior may be attributed to:

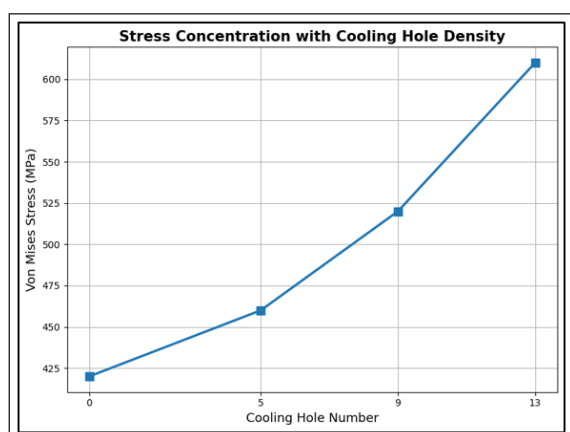
- coolant-air interaction,
- thermal redistribution,
- reduction in effective ligament area,
- and localized flow disturbance around closely spaced holes.

Therefore, the data-driven interpretation confirms that the 5-hole configuration provides the optimum balance between cooling performance and structural stability. The heat-flux contour plots further revealed that the maximum heat flux occurred near the leading-edge stagnation region where direct hot-gas impingement was strongest [13]. The cooling holes effectively reduced local heat transfer by forming a protective coolant-air film over these high-temperature regions.

Table 3: Heat Flux Comparison

Configuration	Inconel 718 (W/mm ²)	Chromium Steel (W/mm ²)
Solid Blade	6.6267	12.979
5-Hole	5.4545	10.744
9-Hole	5.6263	11.120
13-Hole	6.1293	11.865

Graph 4: Stress Concentration vs Cooling Hole Density



Stress and Structural Deformation Analysis

Structural analysis was performed by coupling thermal loading with centrifugal loading conditions corresponding to a rotational speed of 10,000 rpm [14]. The thermo-structural simulations revealed that maximum von Mises stress occurred nearby:

- the blade root,
- cooling-hole edges,
- and coating–substrate interfaces.

These regions experienced severe stress concentration because of combined thermal expansion, centrifugal loading, and geometric discontinuities [15]. Among the investigated materials, Inconel 718 demonstrated the lowest overall stress concentration and deformation values due to its superior high-temperature strength and mechanical stability [16]. Chromium Steel exhibited comparatively higher stress levels and greater deformation because of its reduced thermal resistance and lower creep strength under elevated temperatures. The addition of film-cooling holes influenced stress distribution significantly.

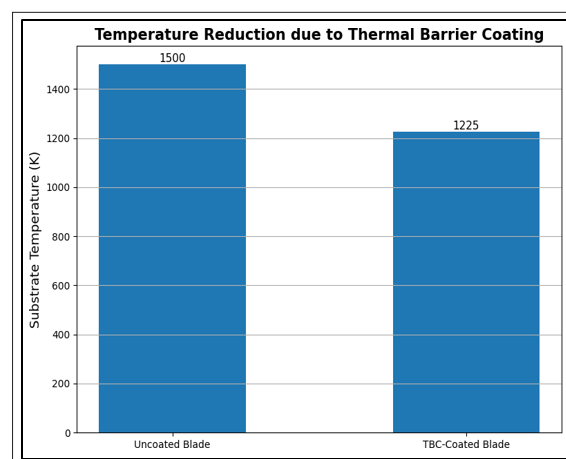
Although cooling holes improved thermal protection, they also introduced localized stress concentration around hole edges due to reduction in effective load-bearing cross-sectional area [17]. The 13-hole configuration exhibited relatively improved temperature reduction in certain regions but generated higher localized stress concentration because of excessive perforation. The total deformation results indicated that maximum displacement occurred near the blade tip region due to centrifugal loading and thermal expansion effects [18]. TBC-coated blades exhibited slightly lower deformation compared to uncoated blades because of reduced thermal penetration into the substrate material. The thermo-structural contour plots clearly demonstrated that optimization of cooling-hole configuration must simultaneously consider:

- thermal protection,
- stress concentration,
- and structural integrity.

Thermal Barrier Coating Performance

The incorporation of the YSZ–MCrAlY Thermal Barrier Coating system significantly improved turbine blade thermal protection capability [19]. The ceramic YSZ top coat acted as an insulating barrier that reduced conductive heat transfer into the substrate material. The finite element simulations indicated that TBC-coated blades experienced substantially lower substrate temperatures compared to uncoated configurations. The thermal resistance provided by the ceramic coating reduced thermal penetration and improved high-temperature operating capability [20]. However, thermo-structural analysis also revealed the development of significant interfacial stresses between the coating and substrate due to mismatch in coefficients of thermal expansion (CTE) [21].

Graph 2: Temperature Reduction due to TBC



During thermal loading, differential expansion between the ceramic layer and metallic substrate generated localized thermal mismatch strain near the coating interface. The analytical calculations and finite element simulations estimated interfacial stress values approaching approximately 500 MPa under severe thermal loading conditions [22]. Such stress concentration may contribute to:

- coating delamination,
- crack initiation,
- thermally grown oxide formation,
- and long-term coating failure.

Despite these limitations, the overall thermo-structural performance of the TBC-coated Inconel 718 blade remained superior compared to uncoated and Chromium Steel configurations. The combination of improved thermal insulation and acceptable structural stability makes TBC-coated Inconel 718 highly suitable for advanced turbine blade applications.

Comparative Thermo-Structural Performance Evaluation

The comparative thermo-structural analysis clearly indicates that material selection and cooling configuration strongly influence turbine blade thermal performance and structural reliability [23]. Among the investigated materials:

- Inconel 718 exhibited the best overall thermo-mechanical performance,
- N-155 alloy demonstrated moderate performance,
- while Chromium Steel showed comparatively poor high-temperature behavior.

The optimized configuration identified in the present study consisted of:

- Inconel 718 substrate material,
- 5-hole film-cooling arrangement,
- and YSZ–MCrAlY Thermal Barrier Coating.

This configuration achieved:

- the lowest heat flux,
- reduced substrate temperature,
- lower von Mises stress,
- improved thermal resistance,
- and acceptable deformation characteristics.

Table 4: Comparative Thermo-Structural Performance

Parameter	Best Configuration
Lowest Heat Flux	Inconel 718 – 5 Hole
Lowest Thermal Stress	Inconel 718 + TBC
Lowest Temperature	TBC-Coated Inconel 718
Highest Structural Stability	Inconel 718
Optimum Cooling Efficiency	5-Hole Configuration

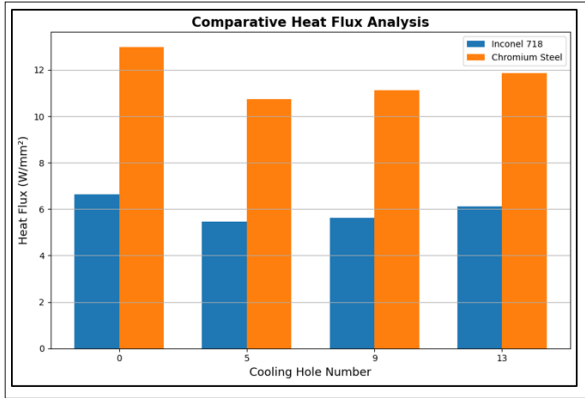
The comparative analysis also demonstrates that increasing cooling-hole density beyond an optimum limit does not linearly improve thermal performance [24]. Instead, excessive perforation introduces structural weakening and localized thermal redistribution effects that reduce overall cooling efficiency. The integration of finite element simulations with data-driven interpretation provides deeper engineering insight into turbine blade optimization compared to isolated thermal or structural analyses [25]. The results obtained in the present investigation establish a comprehensive thermo-structural optimization framework for advanced gas turbine blade cooling systems operating under elevated thermal loading conditions.

Engineering Significance and Industrial Applications

The thermo-structural optimization of gas turbine blades plays a critical role in improving the efficiency, durability, and operational reliability of modern energy-generation and aerospace propulsion systems [1,2]. As turbine inlet temperatures continue to increase in order to achieve higher thermal efficiency and improved power output, the requirement for advanced

cooling technologies and high-temperature materials has become increasingly important [3]. The findings of the present investigation provide valuable engineering insights for the design and development of next-generation turbine blade systems incorporating optimized cooling configurations and Thermal Barrier Coating (TBC) technologies. The results obtained from the finite element simulations demonstrate that the combined application of optimized film cooling, advanced superalloys, and ceramic coating systems can substantially reduce thermal loading, improve structural stability, and enhance service life under severe operating conditions [4]. The optimized Inconel 718 blade with 5-hole cooling configuration and YSZ-based Thermal Barrier Coating exhibited superior thermo-structural performance compared to the other investigated configurations. Such improvements are highly significant for several industrial and engineering applications involving high-temperature turbomachinery systems.

Graph 5: Comparative Heat Flux Analysis



Aerospace Propulsion Systems

One of the most important applications of advanced turbine blade cooling systems is in aerospace propulsion engines used in commercial aircraft, military aircraft, and space propulsion systems [5]. Modern aircraft gas turbines operate under extremely elevated temperatures in order to maximize thrust generation and fuel efficiency. However, such operating conditions generate severe thermal stresses and oxidation effects within turbine blade materials. The optimized thermo-structural framework developed in the present investigation can assist aerospace engineers in designing turbine blades with improved thermal resistance and structural durability [6]. The incorporation of film cooling and Thermal Barrier Coatings reduces substrate temperature and minimizes thermal fatigue, thereby extending blade service life and reducing maintenance frequency. In addition, improved turbine cooling directly contributes to higher turbine inlet temperatures, leading to enhanced engine efficiency, lower fuel consumption, and improved aircraft performance [7]. The use of advanced nickel-based superalloys such as Inconel 718 further improves creep resistance and oxidation resistance under prolonged high-temperature operation.

Thermal Power Plants

Gas turbines are extensively employed in combined-cycle thermal power plants for electricity generation due to their high thermal efficiency and rapid operational response [8]. The performance of turbine blades strongly influences overall plant efficiency, fuel utilization, and operational reliability. The

optimized cooling configurations investigated in the present study can significantly improve thermal protection capability in power-generation turbines operating under continuous high-temperature conditions [9]. Reduction in blade temperature and heat flux decreases the risk of thermal fatigue failure and improves operational stability during long-duration power generation cycles. Furthermore, the application of Thermal Barrier Coatings and optimized film cooling reduces maintenance downtime and replacement costs associated with turbine blade damage [10]. Improved turbine durability ultimately contributes to increased power plant efficiency and lower operational expenditure.

Industrial Gas Turbines

Industrial gas turbines are widely used in petrochemical industries, refineries, offshore platforms, and mechanical drive systems for compressors and pumps [11]. Such turbines often operate continuously under harsh environmental and thermal conditions, making thermal management and structural reliability extremely important. The thermo-structural optimization approach developed in the present investigation provides valuable design guidance for industrial turbine systems exposed to elevated operating temperatures [12]. The reduction in heat flux and thermal stress achieved through optimized cooling-hole configurations can improve long-term turbine reliability and reduce component failure rates. In industries where uninterrupted operation is critical, enhanced turbine blade durability directly improves operational continuity and reduces shutdown-related losses [13].

Aero-Engine Component Optimization

The findings of the present investigation are also relevant for the optimization of other high-temperature aero-engine components such as:

- combustor liners,
- nozzle guide vanes,
- afterburner components,
- and turbine shrouds [14].

The thermo-structural modelling framework developed in this study can be extended to evaluate cooling effectiveness and thermal stress behavior in various aero-engine hot-section components subjected to severe thermal loading. The integration of data-driven interpretation with finite element simulations further enables engineers to optimize cooling performance and material selection for complex turbomachinery systems [15].

Maintenance Reduction and Service Life Enhancement

Thermal fatigue, creep deformation, oxidation, and coating failure are among the primary causes of turbine blade degradation and failure during long-term operation [16]. The incorporation of optimized cooling systems and Thermal Barrier Coatings significantly reduces thermal loading on turbine components, thereby minimizing crack initiation and structural deterioration. The present study demonstrates that optimized film-cooling configurations can effectively lower heat flux and reduce thermal stress concentration under elevated operating conditions [17]. Such improvements directly contribute to:

- longer component service life,
- reduced maintenance frequency,
- lower replacement costs,
- and improved operational reliability.

- In aerospace and power-generation industries, reduced maintenance requirements can produce substantial economic benefits by minimizing operational downtime and improving overall system availability [18].

Fuel Economy and Efficiency Improvement

Improved turbine cooling enables operation at higher turbine inlet temperatures without exceeding material limitations [19]. Since gas turbine efficiency increases with turbine inlet temperature according to Brayton cycle principles, advanced cooling technologies contribute directly to improved fuel economy and thermal efficiency. The optimized thermo-structural configuration identified in the present investigation allows improved thermal protection while maintaining acceptable structural stability [20]. Consequently, turbine systems can operate more efficiently with reduced fuel consumption and improved energy utilization. The application of advanced cooling and coating technologies therefore provides both engineering and economic advantages for modern high-temperature turbine systems operating in aerospace, industrial, and power-generation sectors.

Engineering Significance of Data-Driven Optimization

A major contribution of the present investigation is the integration of data-driven interpretation with thermo-structural finite element analysis [21]. Traditional turbine investigations often rely only on contour-based thermal or stress analysis, whereas the present study incorporates statistical trend evaluation to identify optimum cooling performance and thermal behavior. The regression-based interpretation of heat-flux variation enables improved understanding of nonlinear cooling behavior and optimization trade-offs associated with varying cooling-hole density [22]. Such data-driven optimization frameworks are highly valuable for future smart turbine design systems involving:

- machine learning-assisted optimization,
- AI-based thermal prediction,
- digital twin technology,
- and intelligent turbomachinery diagnostics.

The engineering significance of the present work therefore extends beyond conventional turbine analysis and contributes toward the development of next-generation intelligent thermal management systems for advanced turbine applications.

Sustainability and Energy Implications

The development of efficient and reliable gas turbine systems has become increasingly important in the context of global energy demand, industrial growth, environmental sustainability, and emission reduction targets [1], [2]. Modern gas turbines are widely employed in power generation, aerospace propulsion, marine transportation, and industrial energy systems due to their high power-to-weight ratio, compact design, and superior thermal efficiency [3]. However, increasing turbine inlet temperatures to achieve higher efficiency simultaneously intensifies thermal loading, material degradation, fuel consumption, and maintenance requirements [4]. Therefore, the optimization of turbine blade cooling systems and thermal protection technologies plays a critical role in improving the sustainability and long-term operational efficiency of advanced turbomachinery systems. The present investigation demonstrates that optimized film cooling and Thermal Barrier Coating

(TBC) systems can significantly improve turbine blade thermal protection and structural reliability under elevated operating conditions [5]. The reduction in blade surface temperature and heat flux achieved through optimized cooling configurations contributes directly to improved thermal efficiency and reduced energy loss during turbine operation. By minimizing excessive thermal loading and improving material durability, the proposed thermo-structural optimization framework supports the development of more sustainable and energy-efficient turbine systems.

Improvement in Thermal Efficiency

One of the primary objectives of modern gas turbine engineering is to increase thermal efficiency while maintaining structural reliability under high-temperature operating conditions [6]. According to Brayton cycle principles, gas turbine efficiency increases with higher turbine inlet temperature (TIT). However, elevated temperatures also accelerate thermal degradation and material failure in turbine blade components. The incorporation of optimized film cooling and YSZ-based Thermal Barrier Coatings allows turbine blades to operate safely under higher thermal loads without exceeding material limitations [7]. Reduced thermal penetration into the substrate material enables higher operating temperatures and improved combustion efficiency, thereby increasing overall turbine performance. The optimized Inconel 718 blade configuration identified in the present study demonstrated reduced heat flux and improved thermal resistance, indicating improved capability for high-temperature operation [8]. Such improvements directly contribute to enhanced thermal efficiency and improved energy utilization in gas turbine systems.

Fuel Consumption Reduction

Improved turbine cooling effectiveness and thermal management contribute significantly to fuel economy in both aerospace and power-generation applications [9]. Turbine blades operating at lower substrate temperatures experience reduced thermal degradation and improved aerodynamic stability, enabling more efficient combustion and energy conversion processes. The optimized cooling-hole configuration developed in the present study minimizes thermal loading while maintaining acceptable structural integrity [10]. Efficient thermal protection reduces energy losses associated with excessive heat transfer into turbine components and improves overall engine efficiency. In aerospace propulsion systems, even small improvements in turbine efficiency can produce substantial reductions in fuel consumption over long-duration operation [11]. Similarly, in combined-cycle power plants, improved thermal efficiency directly lowers fuel demand and operational costs. Reduced fuel consumption not only improves economic performance but also contributes to lower greenhouse gas emissions and reduced environmental impact associated with fossil-fuel-based energy systems [12].

Reduction in Greenhouse Gas Emissions

Gas turbine systems operating with improved thermal efficiency require lower fuel input for equivalent power output, thereby reducing carbon dioxide (CO₂) emissions and other harmful combustion products [13]. The optimization of turbine blade cooling systems therefore contributes indirectly to climate-change mitigation and sustainable energy development.

The use of advanced Thermal Barrier Coatings and high-temperature superalloys enables operation at elevated turbine inlet temperatures while maintaining structural durability [14]. Improved combustion efficiency reduces incomplete combustion losses and minimizes pollutant formation during turbine operation. Furthermore, enhanced turbine reliability reduces the frequency of shutdowns, component replacement, and maintenance activities, thereby lowering the environmental impact associated with manufacturing and material consumption [15]. The implementation of advanced thermo-structural optimization strategies in industrial gas turbines and aircraft engines can therefore support global efforts toward cleaner energy production and sustainable industrial operation.

Material Sustainability and Service Life Enhancement

Turbine blade failure due to thermal fatigue, creep deformation, oxidation, and coating degradation leads to increased material consumption, maintenance cost, and industrial waste generation [16]. Improving the durability and operational life of turbine components is therefore essential for sustainable engineering practice. The present investigation demonstrates that the combination of Inconel 718 substrate material, optimized film cooling, and Thermal Barrier Coating significantly reduces thermal stress and deformation under elevated operating conditions [17]. Reduced thermal loading minimizes crack initiation and structural deterioration, thereby extending turbine blade service life.

Longer component life reduces:

- material replacement frequency,
- industrial waste generation,
- manufacturing energy consumption,
- and maintenance-related environmental impact.

The use of durable high-temperature materials and advanced coating systems therefore contributes directly to resource conservation and sustainable industrial operation [18].

Sustainable Aerospace and Power Generation Applications

The aerospace and power-generation sectors are increasingly focusing on sustainable engineering technologies capable of reducing fuel consumption, operational emissions, and lifecycle environmental impact [19]. Advanced gas turbine systems with improved cooling efficiency and thermal protection are essential for achieving these sustainability objectives. The thermo-structural optimization framework developed in the present investigation provides valuable engineering guidance for designing high-efficiency turbine systems suitable for:

- sustainable aircraft propulsion,
- cleaner power-generation systems,
- low-emission industrial turbines,
- and advanced energy-conversion technologies.

The incorporation of data-driven thermo-structural optimization further supports the development of intelligent turbine systems capable of predictive thermal management and operational efficiency enhancement [20].

Contribution Toward Future Sustainable Turbomachinery

Future gas turbine systems are expected to operate at increasingly higher temperatures and efficiency levels in

response to global energy demand and environmental regulations [21]. Consequently, the development of advanced cooling technologies, high-temperature materials, and intelligent optimization frameworks will become increasingly important for sustainable turbomachinery engineering.

The present investigation contributes toward future sustainable turbine development by integrating:

- thermo-structural finite element analysis,
- cooling optimization,
- Thermal Barrier Coating evaluation,
- and data-driven performance interpretation within a unified engineering framework [22].

The findings of this study therefore provide a foundation for future research involving:

- AI-assisted turbine optimization,
- machine-learning-based thermal prediction,
- digital twin technologies,
- and sustainable high-temperature energy systems.

Overall, the thermo-structural optimization strategies investigated in the present work support the advancement of energy-efficient, environmentally sustainable, and technologically advanced gas turbine systems for future aerospace and industrial applications.

Conclusion

The present investigation carried out a comprehensive thermo-structural finite element analysis of gas turbine blades considering the combined influence of material selection, film-cooling configuration, and Thermal Barrier Coating (TBC) systems under elevated operating conditions [1], [2]. The study successfully integrated thermal analysis, structural analysis, thermo-fluid calculations, and data-driven interpretation of simulation outputs within a unified computational framework using ANSYS Workbench. Comparative evaluation was performed for three substrate materials, namely Inconel 718, N-155 alloy, and Chromium Steel, using solid blade and film-cooled blade configurations containing 5, 9, and 13 radial cooling holes. In addition, a YSZ-MCrAlY Thermal Barrier Coating system was incorporated to evaluate coating effectiveness and thermo-mechanical interaction under high-temperature turbine conditions.

The simulation results demonstrated that turbine blade performance is strongly influenced by the combined interaction between thermal conductivity, cooling-hole density, thermo-mechanical loading, and coating behavior [3]. Among the investigated materials, Inconel 718 exhibited the best overall thermo-structural performance due to its superior high-temperature strength, oxidation resistance, lower thermal conductivity, and improved structural stability under elevated operating conditions [4]. Chromium Steel, although economically attractive, experienced comparatively higher heat flux, thermal stress, and structural deformation due to its reduced high-temperature resistance. The incorporation of film-cooling holes significantly improved thermal protection capability by reducing direct thermal exposure to the blade surface. Comparative heat-flux analysis revealed that the 5-hole cooling configuration produced the optimum cooling

performance among all investigated cases. For Inconel 718 blades, heat flux decreased from approximately 6.6267 W/mm² for the solid blade configuration to nearly 5.4545 W/mm² for the 5-hole configuration [5]. However, increasing the number of cooling holes beyond the optimum limit resulted in comparatively smaller thermal improvement and increased structural weakening effects. The data-driven interpretation of simulation outputs demonstrated that turbine cooling behavior follows a nonlinear optimization trend rather than a simple linear relationship with cooling-hole density [6]. Excessive increase in cooling-hole count produced localized thermal redistribution and stress concentration effects, thereby reducing overall cooling efficiency. The regression-based thermo-structural interpretation confirmed that optimum cooling performance requires balancing thermal protection and structural integrity simultaneously. The incorporation of YSZ-based Thermal Barrier Coatings significantly improved thermal insulation capability and reduced substrate temperature by approximately 250–300 K compared to uncoated blade configurations [7]. The ceramic coating effectively minimized conductive heat transfer into the substrate material, thereby improving thermal resistance and operational durability. However, thermo-structural simulations also revealed the development of significant interfacial stresses near the coating–substrate interface due to mismatch in coefficients of thermal expansion (CTE). The calculated thermal mismatch stress approached approximately 500 MPa under elevated operating conditions, indicating the possibility of coating delamination and crack initiation during prolonged thermal cycling [8].

The structural analysis further demonstrated that maximum von Mises stress and deformation occurred nearby:

- the blade root,
- cooling-hole edges,
- and coating interfaces

due to combined centrifugal loading and thermal expansion effects [9]. Nevertheless, the optimized Inconel 718 blade with 5-hole cooling configuration and Thermal Barrier Coating exhibited the most favourable balance between thermal protection, stress distribution, and structural stability. Overall, the present investigation successfully established a comprehensive thermo-structural optimization framework for gas turbine blades operating under elevated thermal and mechanical loading conditions. The combination of:

- Inconel 718 substrate material,
- optimized 5-hole film cooling,
- and YSZ-MCrAlY Thermal Barrier Coating

was identified as the most effective configuration for minimizing heat flux, reducing thermal stress, improving cooling effectiveness, and enhancing turbine blade durability. The integration of finite element simulations with data-driven thermo-structural interpretation provides deeper engineering insight compared to conventional isolated thermal or structural analyses [10]. The findings of the present study therefore contribute significantly toward the development of advanced high-temperature turbine blade systems suitable for aerospace propulsion, industrial gas turbines, and thermal power-generation applications.

Furthermore, the proposed optimization methodology provides a strong foundation for future research involving:

- CFD-assisted cooling analysis,
- AI-based turbine optimization,
- machine-learning thermal prediction,
- and intelligent turbomachinery thermal management systems.

The overall results confirm that integrated thermo-structural optimization combined with advanced cooling and coating technologies can substantially improve the thermal efficiency, operational reliability, sustainability, and service life of modern gas turbine systems operating under severe high-temperature conditions.

Future Scope

Although the present investigation successfully established a comprehensive thermo-structural optimization framework for gas turbine blades using finite element analysis, several opportunities remain for extending and improving the current research in order to achieve more realistic and advanced turbine-performance prediction capabilities [1], [2]. Future developments in computational methods, artificial intelligence, advanced coating technologies, and experimental validation techniques can significantly enhance the accuracy and industrial applicability of turbine blade optimization studies. One of the major future extensions of the present work involves the incorporation of Computational Fluid Dynamics (CFD)-based conjugate heat-transfer analysis [3]. In the current investigation, steady-state thermal analysis was performed using convective boundary conditions. However, detailed CFD simulations can provide improved understanding of coolant-air flow behavior, turbulence interaction, secondary flow structures, and local heat-transfer mechanisms within film-cooling configurations. Advanced turbulence models such as:

- $k-\epsilon$,
- $k-\omega$ SST,
- and Large Eddy Simulation (LES)

can be employed to capture realistic coolant-flow characteristics and improve prediction accuracy under high-temperature turbine operating conditions [4]. Future investigations may also focus on transient thermo-structural analysis instead of steady-state conditions [5]. Gas turbine blades in practical applications experience cyclic thermal loading, startup–shutdown conditions, fluctuating rotational speeds, and transient combustion behavior. Incorporating transient thermal and structural simulations would enable detailed analysis of:

- thermal fatigue,
- cyclic stress variation,
- creep deformation,
- and long-term durability behavior.

Another important extension of the present work involves advanced Thermal Barrier Coating (TBC) modelling [6]. The current study employed a simplified YSZ–MCrAlY coating system; however, future research may investigate:

- multilayer coating systems,
- functionally graded coatings,
- rare-earth ceramic coatings,
- and nano-structured thermal barrier materials.

Detailed modelling of thermally grown oxide (TGO) formation, crack propagation, oxidation kinetics, and coating delamination mechanisms would further improve prediction of coating durability under prolonged high-temperature operation [7]. The integration of Artificial Intelligence (AI), Machine Learning (ML), and optimization algorithms also represents a promising future direction for advanced turbine blade design [8]. AI-assisted optimization techniques can significantly reduce computational cost and improve predictive capability for thermo-structural analysis. Future studies may incorporate:

- artificial neural networks (ANN),
- genetic algorithms (GA),
- support vector machines (SVM),
- and response surface methodology (RSM)

for predictive modelling and automated optimization of cooling configurations, coating thickness, and material selection [9].

Digital twin technology is another emerging research area with significant potential for turbine blade monitoring and predictive maintenance applications [10]. Real-time operational data obtained from turbine systems can be integrated with numerical thermo-structural models to develop intelligent digital replicas capable of:

- thermal monitoring,
- damage prediction,
- life estimation,
- and adaptive cooling optimization.

Experimental validation of finite element simulations is also essential for improving the reliability and industrial acceptance of thermo-structural optimization studies [11]. Future investigations may therefore include:

- wind tunnel testing,
- high-temperature experimental rigs,
- infrared thermography,
- strain gauge measurements,
- and thermal imaging techniques

to validate numerical predictions obtained from computational simulations. Further studies may additionally investigate:

- different cooling-hole geometries,
- shaped film-cooling holes,
- compound-angle injection,
- internal serpentine cooling passages,
- and hybrid cooling systems

to improve cooling effectiveness and minimize aerodynamic losses [12]. In addition, future research can extend the present methodology toward:

- aero-engine nozzle guide vanes,
- combustor liners,
- turbine discs,
- afterburner components,
- and other high-temperature turbomachinery systems.

The integration of sustainability assessment and lifecycle analysis with thermo-structural optimization may also provide valuable insight into environmentally sustainable turbine design and energy-efficient propulsion systems [13]. Overall, the present investigation establishes a strong computational foundation for

future high-temperature turbine blade optimization research. The integration of advanced numerical methods, intelligent optimization techniques, experimental validation, and sustainable engineering approaches can significantly contribute toward the development of next-generation gas turbine systems with improved thermal efficiency, reliability, durability, and environmental performance.

Acknowledgement

The author expresses sincere gratitude to the Department of Mechanical Engineering, Dibrugarh University, Assam, India, for providing academic guidance, technical support, and research facilities necessary for carrying out the present investigation. The author would also like to acknowledge the support provided by faculty members, laboratory staff, and fellow researchers whose valuable suggestions and encouragement contributed significantly to the successful completion of this work. Special appreciation is extended to the developers of ANSYS Workbench and CATIA software platforms utilized for thermo-structural finite element modeling and computational analysis throughout the study. The author further acknowledges the contribution of previous researchers and published scientific literature that provided important theoretical understanding and technical background for the present investigation. Finally, the author expresses heartfelt gratitude to family members and well-wishers for their continuous encouragement, motivation, and support during the completion of this research work [72-75].

References

1. Deepanraj B, Lawrence P, Sankaranarayanan G. Theoretical analysis of gas turbine blade by finite element method. *Scientific World*. 2011. 9: 29-33.
2. Lakshminarayana B. *Fluid Dynamics and Heat Transfer of Turbomachinery*. Wiley-Interscience. 1996.
3. ANSYS Inc. *ANSYS Workbench User's Guide*. ANSYS Inc. 2023.
4. Miller RA. Current status of thermal barrier coatings-An overview. *Surface and Coatings Technology*. 1987. 30: 1-11.
5. Padture NP, Gell M, Jordan EH. Thermal barrier coatings for gas-turbine engine applications. *Science*. 2002. 296: 280-284.
6. Clarke DR, Levi CG. Materials design for the next generation thermal barrier coatings. *Annual Review of Materials Research*. 2003. 33: 383-417.
7. Evans AG, Mumm DR, Hutchinson JW, Meier GH, Pettit FS. Mechanisms controlling the durability of thermal barrier coatings. *Progress in Materials Science*. 2001. 46: 505-553.
8. Goldstein RJ. Film cooling. *Advances in Heat Transfer*. 1971. 7: 321-379.
9. Han JC, Dutta S, Ekkad S. *Gas Turbine Heat Transfer and Cooling Technology*. Taylor & Francis. 2000.
10. Bunker RS. A review of shaped hole turbine film-cooling technology. *Journal of Heat Transfer*. 2005. 127: 441-453.
11. Bogard DG, Thole KA. Gas turbine film cooling. *Journal of Propulsion and Power*. 2006. 22: 249-270.
12. Li X, Kassab AJ. Optimization of gas turbine blade cooling passages using computational methods. *Applied Thermal Engineering*. 2010. 30: 2348-2357.
13. Jha R. Analysis of cooling techniques for turbine blades. *International Journal of Engineering Research and Technology*. 2015. 4: 876-881.
14. Zhou Y, Zhao X, Li J. Thermal barrier coatings for gas turbine applications. *Ceramics International*. 2017. 43: 1-12.
15. Rao YV, Kumar M, Singh P. Conjugate heat transfer analysis of turbine blades. *Applied Thermal Engineering*. 2018. 132: 312-321.
16. Singh A, Kumar R. Structural analysis of film-cooled gas turbine blades. *Materials Today: Proceedings*. 2019. 18: 4567- 4575.
17. Zhu D, Miller RA. Thermal conductivity and elastic modulus evolution of thermal barrier coatings under high heat flux conditions. *Journal of Thermal Spray Technology*. 1998. 7: 175-180.
18. Levi CG. Emerging materials and processes for thermal barrier systems. *Current Opinion in Solid State and Materials Science*. 2004. 8: 77-91.
19. Meher-Homji CB. Gas turbine axial compressor fouling and washing. *Proceedings of the 29th Turbomachinery Symposium*. 2000:163-191.
20. Boyce MP. *Gas Turbine Engineering Handbook*. 4th ed. Elsevier. 2012.
21. Mattingly JD. *Elements of Gas Turbine Propulsion*. AIAA Education Series. 2005.
22. Turns SR. *An Introduction to Combustion: Concepts and Applications*. 3rd ed. McGraw-Hill. 2012.
23. Versteeg HK, Malalasekera W. *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*. Pearson Education. 2007.
24. Incropera FP, DeWitt DP, Bergman TL, Lavine AS. *Fundamentals of Heat and Mass Transfer*. 7th ed. Wiley. 2011.
25. Holman JP. *Heat Transfer*. 10th ed. McGraw-Hill. 2010.
26. Anderson JD. *Fundamentals of Aerodynamics*. 5th ed. McGraw-Hill. 2011.
27. Cengel YA, Ghajar AJ. *Heat and Mass Transfer: Fundamentals and Applications*. 5th ed. McGraw-Hill. 2015.
28. Callister WD, Rethwisch DG. *Materials Science and Engineering: An Introduction*. 10th ed. Wiley. 2018.
29. Dieter GE. *Mechanical Metallurgy*. 3rd ed. McGraw-Hill. 1986.
30. ASM International. *Properties and Selection: Irons, Steels, and High-Performance Alloys*. ASM Handbook. 1: 990.
31. Schlichting H, Gersten K. *Boundary Layer Theory*. 9th ed. Springer. 2016.
32. Kays WM, Crawford ME. *Convective Heat and Mass Transfer*. 3rd ed. McGraw-Hill. 1993.
33. Boresi AP, Schmidt RJ. *Advanced Mechanics of Materials*. 6th ed. Wiley. 2003.
34. Timoshenko SP, Goodier JN. *Theory of Elasticity*. 3rd ed. McGraw-Hill. 1970.
35. Shigley JE, Mischke CR. *Mechanical Engineering Design*. 6th ed. McGraw-Hill. 2001.
36. Bejan A. *Convection Heat Transfer*. 4th ed. Wiley. 2013.
37. Fletcher LS. Recent developments in heat transfer. *International Journal of Heat and Mass Transfer*. 1984. 27: 1-12.
38. Ekkad SV, Han JC. Detailed heat transfer distributions in two-pass square channels with rib turbulators. *International Journal of Heat and Mass Transfer*. 2000. 43: 3205-3215.

39. Dunn MG. Convective heat transfer and aerodynamics in axial flow turbines. *Journal of Turbomachinery*. 2001. 123: 637-686.
40. Metzger DE. Heat transfer in gas turbine systems. *Annals of the New York Academy of Sciences*. 1985. 469: 1-15.
41. Ramesh G, Prakash S. Thermal analysis of gas turbine blade using finite element method. *International Journal of Emerging Technology and Advanced Engineering*. 2014. 4: 575-581.
42. Saini RP, Saini JS. Development of correlations for Nusselt number and friction factor. *International Journal of Heat and Mass Transfer*. 2008. 51: 3987-3999.
43. Koff BL. Gas turbine technology evolution: A designer's perspective. *Journal of Propulsion and Power*. 2004. 20: 577-595.
44. Heidmann JD, Ekkad SV. A novel antifouling film cooling design for turbine blades. *ASME Turbo Expo Proceedings*. 2008: 431-440.
45. Choi SR, Zhu D. Fracture behavior of thermal barrier coatings. *Engineering Fracture Mechanics*. 2005. 72: 1606-1638.
46. Reed RC. *The Superalloys: Fundamentals and Applications*. Cambridge University Press. 2006.
47. Sims CT, Stoloff NS, Hagel WC. *Superalloys II*. Wiley-Interscience. 1987.
48. Pollock TM, Tin S. Nickel-based superalloys for advanced turbine engines. *Journal of Propulsion and Power*. 2006. 22: 361374.
49. Boyer HE. *Atlas of Stress-Strain Curves*. ASM International. 1987.
50. Syed Eirfan Atthar. Modelling and Analysis of Suspension System Under Mechanical Loads: A Comprehensive Analysis Under Mechanical Loads. *IJNRD*. 2024. 9: 2456-4184.
51. Lefebvre AH, Ballal DR. *Gas Turbine Combustion: Alternative Fuels and Emissions*. 3rd ed. CRC Press. 2010.
52. Dixon SL, Hall CA. *Fluid Mechanics and Thermodynamics of Turbomachinery*. 7th ed. Butterworth-Heinemann. 2014.
53. Kurzke J, Halliwell I. *Propulsion and Power: An Exploration of Gas Turbine Performance Modeling*. Springer. 2018.
54. Saravanamuttoo H, Rogers G, Cohen H, Straznicki P. *Gas Turbine Theory*. 6th ed. Pearson Education. 2009.
55. Walsh PP, Fletcher P. *Gas Turbine Performance*. 2nd ed. Blackwell Science. 2004.
56. Kerrebrock JL. *Aircraft Engines and Gas Turbines*. MIT Press. 1992.
57. Hill P, Peterson C. *Mechanics and Thermodynamics of Propulsion*. 2nd ed. Addison-Wesley. 1992.
58. Çengel YA, Boles MA, Kanoglu M. *Thermodynamics: An Engineering Approach*. 9th ed. McGraw-Hill Education. 2019.
59. White FM. *Fluid Mechanics*. 8th ed. McGraw-Hill Education. 2016.
60. Fox RW, McDonald AT, Pritchard PJ, Leylegian JC. *Introduction to Fluid Mechanics*. 9th ed. Wiley. 2015.
61. Moran MJ, Shapiro HN, Boettner DD, Bailey MB. *Fundamentals of Engineering Thermodynamics*. 8th ed. Wiley. 2014.
62. Rogers GFC, Mayhew YR. *Engineering Thermodynamics: Work and Heat Transfer*. 4th ed. Longman Scientific & Technical. 1992.
63. Kutz M. *Mechanical Engineers' Handbook: Energy and Power*. 4th ed. Wiley. 2018.
64. Boyer R, Welsch G, Collings EW. *Materials Properties Handbook: Titanium Alloys*. ASM International. 1994.
65. Donachie MJ, Donachie SJ. *Superalloys: A Technical Guide*. 2nd ed. ASM International. 2002.
66. Davis JR. *Nickel, Cobalt, and Their Alloys*. ASM International. 2000.
67. Nitin P, Jordan EH, Gell M. Thermal barrier coatings in gas turbine applications. *MRS Bulletin*. 2001. 26: 27-31.
68. Hassan I, Yuki U. Numerical investigation of film cooling effectiveness in gas turbine blades. *Applied Thermal Engineering*. 2016. 102: 1265-1275.
69. Han JC, Rallabandi AP. Turbine blade internal cooling passages and heat transfer enhancement. *Heat Transfer Engineering*. 2010. 31: 465-481.
70. Martini P, Schulz A, Bauer HJ, Whitney CF. Film cooling and heat transfer on turbine blades. *ASME Journal of Turbomachinery*. 2003. 125: 393-401.
71. Bunker RS. Evolution of gas turbine cooling. *Journal of Turbomachinery*. 2017. 139: 041001.
72. Wright IG, Gibbons TB. Recent developments in gas turbine materials and technology. *International Journal of Pressure Vessels and Piping*. 2007. 85: 73-80.
73. Darolia R. Thermal barrier coatings technology: Critical review and future directions. *International Materials Reviews*. 2013. 58: 315-348.
74. Srivastava R, Chandra S. Thermo-structural analysis of gas turbine blade using ANSYS. *Materials Today: Proceedings*. 2020. 26: 1931-1937.
75. Prasad BVSSS, Rao DN. Finite element thermal analysis of gas turbine blade with cooling holes. *International Journal of Mechanical Engineering and Technology*. 2019. 10: 245-254.