Numerical Investigation on Effect of Thermal Barrier Coatings on Gas Turbine Combustor

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Abstract—Thermal barrier coatings (TBCs) are critical for enhancing the performance and durability of gas turbine combustors by insulating metal components from extreme combustion temperatures. This project aims to conduct a comprehensive numerical investigation to evaluate the effects of TBCs on the thermal and fluid dynamics within gas turbine combustors. By using computational fluid dynamics (CFD) and heat transfer simulations, the study will analyze how different TBC materials, thicknesses, and configurations impact the overall combustion performance, including temperature distribution, thermal stresses, and efficiency. The study will simulate various operating conditions to investigate the behavior of coated and uncoated turbine surfaces. Key objectives include determining the reduction in surface temperatures of turbine blades, evaluating thermal gradient control, and assessing the influence of TBCs on component life and fuel efficiency. The results provide insights into optimizing TBC applications to enhance gas turbine performance and durability. The obtained results provided insights into the optimal application of TBCs and various materials as TBC, highlighting their potential to extend component lifespan and enhance gas turbine efficiency. This investigation will contribute to the ongoing efforts in improving gas turbine technology, with implications for aerospace and power generation sectors, ultimately leading to more sustainable and efficient energy solutions.

***Keywords—Thermal Barrier Coatings, Gas Turbine Combustor, Computational Fluid Dynamics, Heat Transfer, Thermal Management, Combustor Efficiency*.**

I. INTRODUCTION

Thermal barrier coatings (TBCs) have revolutionized the field of materials science and engineering, providing critical protection for high-temperature components in various industries, particularly aerospace and power generation. These coatings, designed to insulate surfaces from excessive heat, have evolved significantly over the decades, driven by advancements in materials science, manufacturing techniques, and the increasing demands of modern applications. The concept of using coatings to protect surfaces from high temperatures dates back to ancient civilizations. Early examples include the use of glazes on pottery to prevent cracking and the application of protective layers on metal tools. However, the development of TBCs as we know them today began in earnest during the mid-20th century, primarily driven by the aerospace industry's need for materials capable of withstanding the extreme temperatures generated by jet engines. Initial TBCs were primarily composed of ceramic materials, such as alumina and zirconia, which offered excellent thermal insulation properties. These early coatings were applied using techniques like plasma spraying, which involved spraying molten ceramic particles onto the substrate surface. While effective, these early TBCs suffered from limitations, including low fracture toughness and susceptibility to degradation under cyclic loading conditions. In the 1980s and 1990s, significant advancements were made in TBC technology. The development of partially stabilized zirconia (PSZ) coatings, which exhibited improved fracture toughness and resistance to thermal shock, marked a major breakthrough. Additionally, the introduction of bond coat layers between the substrate and the TBC helped to enhance adhesion and prevent interdiffusion.

Today, TBCs are used in a wide range of applications, including gas turbine engines, and industrial furnaces. These coatings offer numerous benefits, such as increased component life, improved fuel efficiency, and reduced emissions. As technology continues to advance, we can expect to see further developments in TBC technology.

II. BACKGROUND

Thermal Barrier Coatings (TBCs) emerged in the 1950s to protect high-temperature components in gas turbines and aerospace applications. Studies focus on various coating materials, and their thermal conductivity, thermal expansion properties, and adhesion strength. The scope encompasses assessing the impact of TBCs on heat transfer, combustion stability, and emission reductions under different operating

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conditions. Methods include computational fluid dynamics (CFD) simulations to model the heat transfer and flow characteristics in combustors with and without TBCs. The investigation aims to optimize TBC application techniques and explore new materials for improved performance in advanced gas turbine systems.

Literature Survey

Zhou et al. [1] examined the thermal performance of Yttria-stabilized zirconia (YSZ) TBCs in gas turbine applications. They found that the application of TBCs significantly improved the thermal efficiency of combustors by reducing heat transfer to the underlying materials, thus enhancing the overall lifespan of the components. Gupta et al. [2] focused on the mechanical properties of TBCs and their influence on the performance of gas turbine combustors. The study introduced a finite element model that simulated thermal and mechanical stresses in coated components. The results indicated that TBCs could effectively mitigate stress concentration points, leading to improved performance metrics and reduced failure rates in combustor components.

Huang et al. [3] conducted a numerical investigation into the effectiveness of TBCs in reducing thermal stresses in gas turbine combustors. Their findings indicated that TBCs not only lowered the temperature gradient across the component surfaces but also effectively mitigated thermal fatigue failures, thereby increasing reliability. J. D. Wright and R. P. Smith [4] analyzed the impact of various deposition techniques on the micro-structure of TBCs. Their work emphasized how methods like plasma spraying and electron beam physical vapor deposition (EB-PVD) resulted in different micro-structural properties that affect thermal performance and longevity. They concluded that optimizing deposition techniques could enhance TBC performance, ultimately benefiting gas turbine efficiency.

C.F.Huang et al. [5] investigated the long-term performance of TBCs under cyclic thermal loads. Their research established that TBCs not only provide thermal insulation but also improve fatigue resistance in gas turbine combustors. They conducted long-term testing and found that TBCs significantly reduce the rate of thermal fatigue failure, allowing for longer operational cycles and reduced maintenance needs. Sullivan et al. [6] explored the impact of TBCs on emissions from gas turbines. Their study revealed that the application of TBCs could lead to a reduction in nitrogen oxides (NOx) emissions by optimizing the combustion temperature profiles within the combustor, resulting in improved environmental performance.

Li et al. [7] focused on the optimization of TBC materials for high-temperature applications. Their research highlighted that advanced TBC materials, such as ceria-based coatings, offered superior thermal insulation properties and could withstand higher temperatures, thus improving the efficiency and durability of gas turbine combustors. Kumar et al. [8] investigated the microstructural characteristics of TBCs and their effect on thermal conductivity. They demonstrated that the microstructural features, including porosity and grain size, significantly influenced the thermal conductivity of TBCs, which in turn affected the thermal protection of combustor components.

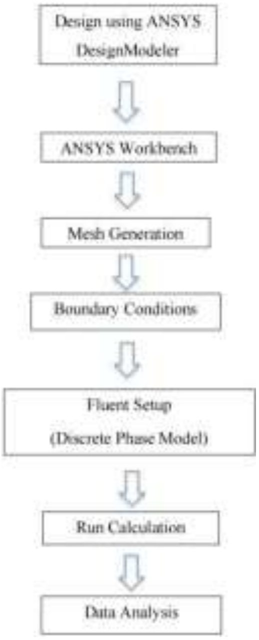
Khan et al. [9] investigated the thermal performance of gas turbine components coated with zirconia-based TBCs. They demonstrated that the application of these coatings significantly enhanced the thermal efficiency and longevity of combustor materials by providing effective insulation against high-temperature gases. Their findings highlighted the importance of optimizing the coating thickness for achieving optimal thermal protection. Patel et al. [10] studied the long-term performance of TBCs under simulated operational conditions. Their findings suggested that TBCs experienced degradation over time due to thermal cycling, yet the performance was notably better compared to uncoated surfaces, thus validating the use of TBCs for enhanced combustor performance.

Narayana et al. [11] developed a computational fluid dynamics (CFD) model to analyze the heat transfer characteristics of TBCs in gas turbines. The model indicated that TBCs not only improved thermal protection but also influenced the flow patterns within the combustor, leading to better mixing and combustion efficiency. Alfaro et al. [12] performed a comparative study of various TBC compositions and their effects on thermal and mechanical performance. Their research established that the choice of TBC material significantly impacted the thermal barrier effectiveness and durability, suggesting tailored approaches for specific combustor designs. Wang et al. [13] presented a comprehensive review of advanced TBCs, including multi-layer coatings and nanostructured materials. Their findings suggested that innovative TBC designs could further enhance thermal performance and longevity in high-temperature gas turbine applications, thereby advancing combustion technology.

Nguyen et al. [14] examined the long-term performance of TBCs under cyclic thermal loading conditions. They employed a life prediction model to assess the reliability of various coating materials over extended operational periods. The results indicated that coatings with improved thermal shock resistance exhibited a longer lifespan, thereby reducing maintenance costs. Their work provided crucial insights into the life expectancy of TBCs in demanding operational environments. Singh et al. [15] utilized experimental and computational methods to analyze the thermal behavior of gas turbine combustors with TBCs. Their study confirmed that TBCs effectively lowered the surface temperatures of combustor components and contributed to improved thermal efficiency, highlighting the need for further research on TBC durability under operational conditions.

III. METHODOLOGY

The methodology for the numerical investigation of the effect of thermal barrier coating (TBC) on a gas turbine combustor involves a series of computational simulations and analyses. First, a detailed 3D model of the gas turbine combustor section, including relevant geometrical features, is developed using ANSYS-DesignModeler software. Next, the physical properties of the combustor materials and TBC are defined, including thermal conductivity, specific heat, and thickness. The model is then imported into a computational fluid dynamics (CFD) software where boundary conditions, such as inlet temperatures, pressure, fuel-air mixture, and combustion parameters, are set.To estimate the erosion rate of selected TBC materials, discrete phase model (DPM) is used. The numerical solver is run to simulate the thermal, flow behavior and erosion rate in the combustor with and without the TBC, focusing on the temperature distribution, heat flux, and thermal stresses. Post- processing is carried out to analyze and compare the results, identifying the influence of the TBC on improving thermal efficiency, reducing metal temperatures, and enhancing the overall performance of the combustor.



1. Design

The numerical investigation of thermal barrier coatings (TBCs) on a gas turbine combustor involves several key steps to accurately simulate the thermal performance and durability of these coatings. We have developed a detailed geometric model of the gas turbine combustor section with a fluid volume including the liner, binder and thermal barrier coating.

Fig.*1 2D view of combustor test section*

In this study, we analyze the performance of TBC by considering different geometry models like:

1. Fluid Volume Without Thermal Barrier Coating (TBC)
2. Fluid Volume With Thermal Barrier Coating (TBC)
3. Variation of TBC Thickness with Respect to Liner Thickness.

These cases are crucial in evaluating the effectiveness of the TBC in reducing thermal loads, improving durability, and ensuring the safety and efficiency of gas turbine combustor walls.

Table.1 Dimensions of geometry considered

Geometry	Fluid Volume (in mm^3)	TBC thickness (in mm)	Binder thickness (in mm)	Liner thickness (in mm)
Model-1	100x100x60	2	1.5	3
Model-2	100x100x60	3	1.5	2

Only two geometries—where the TBC thickness is greater than the liner thickness, and vice versa—are considered to evaluate the effectiveness of TBC in gas turbine combustors because these configurations cover the essential trade-offs between thermal insulation and mechanical strength. The goal is to ensure that the TBC and liner work together to protect the combustor under varying thermal and mechanical loads without compromising performance, weight, or durability. These geometries represent optimal conditions for evaluating and balancing thermal protection and structural integrity in a gas turbine engine's combustor design.

2. Mesh Data

Meshing in ANSYS refers to the process of dividing a geometric domain into smaller, manageable elements or cells to facilitate numerical analysis.The meshing for the geometry is done in Ansys Meshing software and then imported to the fluent solver.

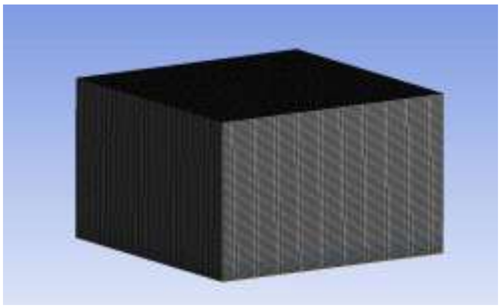


Fig.*2 Meshing of combustor test section with TBC*

3. Setup - Discrete Phase Model (DPM) in Fluent

In Discrete Phase Model (DPM) analysis is used to assess the performance of thermal barrier coatings (TBCs) because it provides detailed insights into the interaction of discrete particles, such as debris, molten droplets, or dust, with the coating material in high-temperature environments. This analysis helps evaluate the erosion, deposition, and thermal protection characteristics of TBCs under conditions like gas turbine or jet engine operations. By simulating particle trajectories, erosion rate, particle wear and tear, flux mechanisms, heat transfer, mass flow rate of particles and impingement effects, DPM aids in understanding the durability, thermal resistance, and failure mechanisms of the coatings, ultimately contributing to the optimization of their design, performance behaviour, efficiency and material composition.

4. *Erosion Rate*

In the Discrete Phase Model (DPM) within ANSYS Fluent, the erosion rate refers to the material loss from a surface due to the impact of particles suspended in the continuous phase (typically a gas or liquid). These particles can strike surfaces at varying angles and velocities, causing material removal. The DPM tracks these particle trajectories and computes the erosion rate based on particle-surface interactions. The erosion rate in the Discrete Phase Model (DPM) in ANSYS Fluent is calculated based on the impact force of particles on a solid surface. The model assumes that the impact force is proportional to the kinetic energy of the particle and the contact area between the particle and the surface.

Fluent uses the following general formula to calculate the erosion rate Ė for each particle impact on a surface:

$$\dot{E} = C.f(\theta).\ \left(\frac{U_p}{U_{ref}}\right)^n.m_p$$

where:

- $\dot{E}$ = erosion rate (typically mass loss per unit time, e.g., kg/s),
- C = erosion constant (material-specific empirical constant),
- $f(\theta)$= angle-dependent function for the erosion rate,
- v_p = impact velocity of the particle,
- U_{ref} = reference velocity (used to normalize the velocity term),
- n = velocity exponent (determined experimentally, often ranging from 2 to 3),
- m_p = mass of the particle

Fluent sums the contributions of each individual particle impact over time to provide a cumulative erosion rate for surfaces. The total erosion rate for a surface can be written as:

$$\dot{E}_{total} = \sum \dot{E}_i$$

Where, $\dot{E}_i$ is the erosion rate due to the *i*-th particle impact.

5. *Boundary Conditions*

In erosion rate analysis, boundary conditions are critical for accurately simulating the interactions between particles, fluid, and the surface. The inlet of the combustion chamber and inlet of cooling holes are considered as the velocity inlet with mass flow rate and initial particle velocity; the outlet is the pressure outlet. The standard wall conditions are applied at the walls.
The inlet conditions to a gas turbine engine combustor significantly influence its performance, emissions, and durability.

Table.2 Inlet conditions of Combustor[16]

Temperature	900 K
Pressure	486233 Pa
Air-fuel ratio	0.07
Mass flow rate	0.55 kg/s
Velocity	312 m/s

Cooling holes are critical components of gas turbine combustors, designed to protect the combustor walls from excessive heat. They achieve this by introducing cooler air into the combustion chamber, forming a protective film along the walls.

Table.3 Air conditions through Cooling Holes[17]

Temperature	500 K
Pressure	206833 Pa
Mass flow rate	1.55 kg/s
Velocity	400 m/s

6. *Initialisation and Solution*

The simulation is run over several iterations, typically on the order of 500 to 1000 to achieve convergence. The residuals for continuity, momentum, energy, and species transport are monitored, with convergence criteria set at 1e-6. Throughout the iterations, key outputs such as temperature profiles, velocity fields, and pressure distributions are collected.

IV. RESULTS AND DISCUSSION

A temperature contour is a visual representation that shows how temperature varies across a surface or region using lines or color gradients. An erosion rate contour is a graphical representation that shows the variation of erosion rate over a surface or region.

1. Fluid Volume without TBC

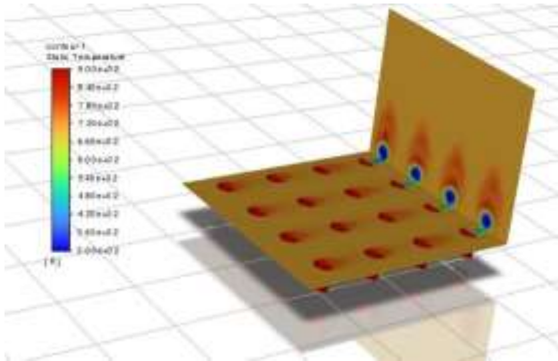


Fig.3 Temperature contour

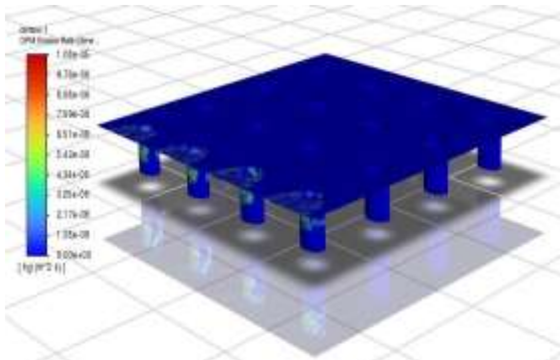


Fig.4 Erosion rate contour

2. Fluid Volume with TBC

Case 1 : The fluid volume geometry considered in this case is of model-1 i.e, higher liner thickness and lower TBC thickness. Analysis is done by considering these variations accordingly.

a) Cobalt-Aluminide alloy : The aluminium alloy is considered as a TBC material and the results are analyzed.

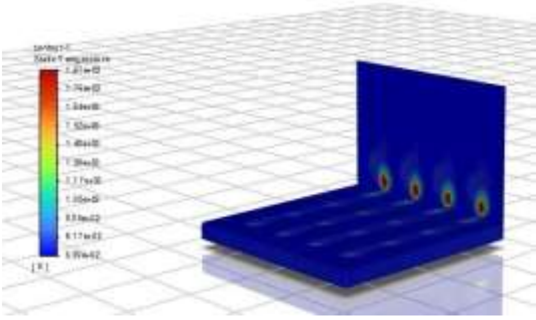


Fig.5 Temperature contour

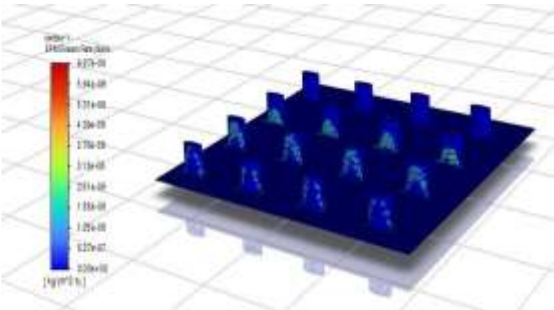


Fig.6 Erosion rate contour

b) Nickel-Yttrium alloy: The nickel alloy is considered as a TBC material and the results are analyzed.

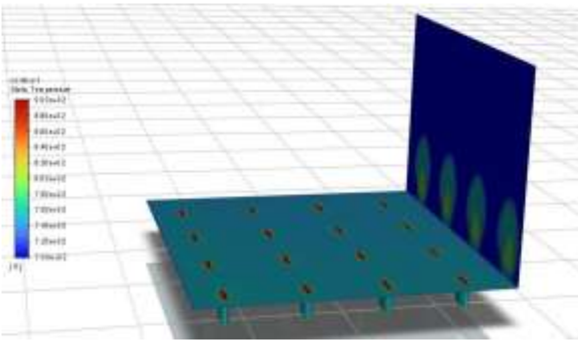


Fig.7 Temperature contour

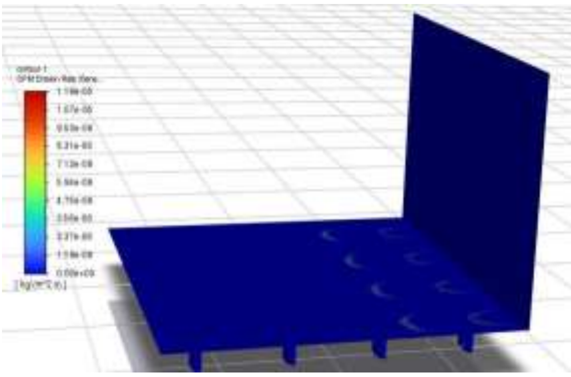


Fig.8 Erosion rate contour

Case 2 : The fluid volume geometry considered in this case is of model-2 i.e, higher TBC thickness and lower liner thickness.

a) Cobalt-Aluminide alloy :

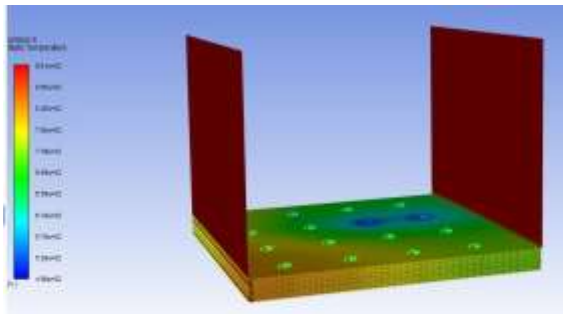


Fig.9 Temperature contour

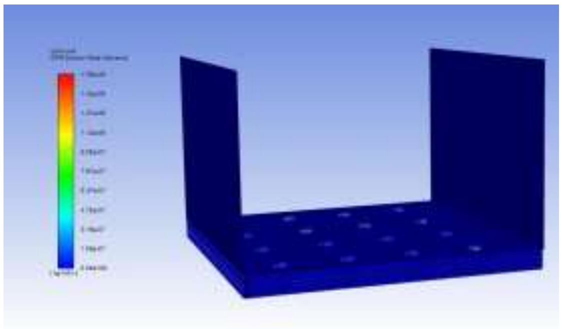


Fig.10 Erosion rate contour

b) Nickel-Yttrium alloy

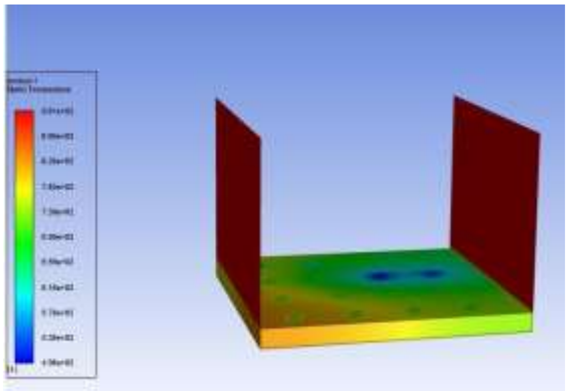


Fig.11 Temperature contour

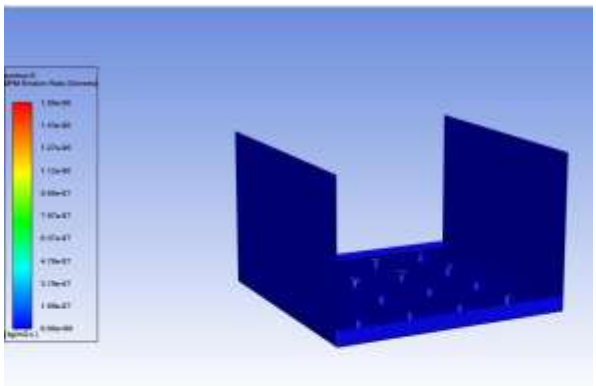


Fig.12 Erosion rate contour

Different temperature rates and erosion rates are obtained in all the cases. All the results are comparatively studied to choose the suitable material as TBC.In the analysis of temperature and erosion resistance of thermal barrier coatings (TBCs) in a gas turbine combustor, the findings reveal significant differences among the materials tested. Without TBC, the system can only tolerate temperatures between 300 K and 900 K. However, Cobalt Aluminide (Case 1) demonstrates exceptional heat resistance, raising the maximum effective temperature to 1870 K, far exceeding that of other coatings. In contrast, Nickel-Yttrium (Case 1) offers limited protection, with a maximum temperature capped at 900 K, similar to the uncoated scenario. Both Cobalt Aluminide (Case 2) and Nickel-Yttrium (Case 2) provide moderate temperature protection, with maximum temperatures ranging from 902 K to 910 K. Regarding erosion resistance, the uncoated configuration shows the highest erosion rate at 1.08×10^{-5} kg/m²s. Cobalt Aluminide (Case 1) exhibits a significantly lower erosion rate of 6.27×10^{-6} kg/m²s, indicating robust resistance to physical wear, while Nickel- Yttrium (Case 1) has a higher erosion rate of 1.19×10^{-5} kg/m²s, making it less effective against wear compared to Cobalt Aluminide.

In Case 2, both coatings improve their erosion resistance, with Cobalt Aluminide showing 1.59×10^{-6} kg/m²s and Nickel-Yttrium at 1.69×10^{-6} kg/m²s, but Cobalt Aluminide still slightly outperforms Nickel-Yttrium in terms of erosion resistance.

V. CONCLUSION AND FUTURE SCOPE

The numerical investigation highlights the effectiveness of thermal barrier coatings (TBCs) in gas turbine combustors, demonstrating improved thermal efficiency, reduced fuel consumption, and prolonged component life. Cobalt-Aluminide Alloy TBC (Case 1) emerged as the most effective material, offering the highest temperature resistance (1870K) and low erosion rates, making it ideal for high-temperature environments. TBCs significantly reduce thermal stresses, mitigating fatigue and creep, thus extending turbine durability. Future advancements may include refined computational models, exploration of new materials, multi-layered coatings, and additive manufacturing to further enhance performance, efficiency, and sustainability in gas turbine systems.

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