Innovations in Blade Materials and Cooling Systems: A Technical Review

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Abstract. Aero-engines and industrial gas turbines are critical technologies that reflect a nation's industrial technological advancement. The continuous rise in turbine inlet temperature (TIT) has significantly enhanced their performance but also imposes extreme thermal stresses on turbine blade. This review explores the evolution of air-cooled turbine blades, emphasizing the growing role of advanced materials and innovative cooling strategies. It also discusses key design parameters and the fundamental principles of computational fluid dynamics (CFD in optimizing thermal management. Finally, the study outlines future research directions, highlighting potential breakthroughs to address the aerothermal and mechanical challenges of next-generation gas turbines.

Keywords: CFD, Turbine blades, Blade cooling, Cooling mechanisms, Aerothermal engineering.

1 Introduction

Turbine blades are subjected to extreme constraints like centrifugal forces, aero-dynamic impacts, and high temperature, making them highly susceptible to failure. The efficiency of gas turbines largely relies on the increase in turbine inlet temperature (TIT); however, this temperature increase is achieved through rich and lean combustion modes, which produce hot spots and strong vortices [1]. These influences, combined with centrifugal influences, create a highly unsteady flow, with a temperature that by far exceeds material resistance limits. These harsh conditions create severe thermal gradients, promoting the development of localized stresses that reinforce thermal fatigue phenomena and the potential for premature component failure [2]. These failures lead to unexpected shutdowns and entail expensive operating costs, undermining gas turbine reliability and durability. In order to surmount these issues, researchers have developed materials with low thermal conductivity and advanced cooling systems for controlling blade temperature more efficiently, reducing thermal stresses, and extending their service life.

To address thermal challenges, gas turbines incorporate advanced cooling systems that regulate the temperature of critical components within permissible limits. Cooling air,

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sourced from the final stage of the compressor, is channelled to the turbine disks and blades through secondary air systems (SAS). Once introduced, this cooling air navigates complex internal passages within the blades, where strategically designed geometries increase the heat transfer surface area and induce turbulence, thereby enhancing overall cooling efficiency. [3,4]

This paper provides a comprehensive review of the latest developments and technological advancements in gas turbine cooling technologies. It begins by examining the significant rise in turbine inlet temperatures over the past decades and the associated thermal and mechanical challenges faced by modern turbomachinery. The study then presents research findings on various cooling techniques, including film cooling, transpiration cooling, and convective cooling, along with the development of advanced materials designed to withstand extreme operating conditions. Additionally, numerical methods used to model these phenomena are discussed, with a particular focus on computational fluid dynamics (CFD) and its application in simulating complex flow and heat transfer processes. Finally, the paper highlights future challenges and research directions aimed at further enhancing the efficiency and durability of gas turbine cooling systems.

2 Evolution of turbine inlet temperature

The progression of turbine inlet temperature (TIT) over the past decades reflects significant advancements in gas turbine technology, particularly in terms of performance and efficiency. Early gas turbines, equipped with non-cooled blades, were limited to a TIT of approximately 1050 K due to material constraints. However, the introduction of internal convective cooling in the 1960s, notably with the Rolls-Royce Conway engine, marked a turning point, enabling TIT to exceed the thermal limits of nickel-based superalloys. This upward trend continued, with an average annual in-crease of 10 K in TIT, outpacing the incremental rise in the maximum allowable temperature of superalloys, which advanced by only 3 K per year. To bridge this gap, revolutionary thermal protection techniques were introduced, including active cooling (internal cooling and film cooling) and passive thermal barrier coatings (TBCs), which contributed to temperature reductions of up to 170 K.

Currently, TIT exceeds the melting point of blade materials by more than 350 K, made possible through advancements in superalloys technology, ranging from forged alloys to single-crystal structures, as well as optimized cooling systems. These innovations have enabled modern engines, such as the Rolls-Royce Trent family, to generate 60 times the thrust of early jet engines while simultaneously tripling the thrust-to-weight ratio and halving specific fuel consumption [5].

To meet future demands for high-efficiency, low-emission gas turbines, further advancements in cooling system design and next-generation materials will be essential, ensuring continued improvements in TIT and overall performance.

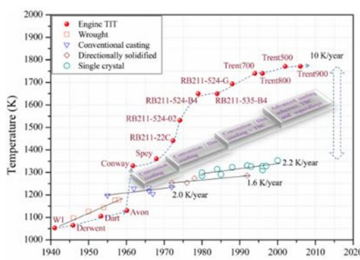

Fig. 1. Development of the TIT of Rolls Royce's thermal protection systems for civil aero-engines [6]

3 Description of turbomachinery challenges

Achieving high efficiency and specific power while maintaining material constraints and machine reliability is a key objective in the design of modern gas turbines. Additionally, over the past decades, increasing attention has been given to reducing pollutant emissions such as unburned hydrocarbons, nitrogen oxides (NOx), and sulfur oxides (SOx), which necessitates a better understanding of the interaction between gas turbine components. The performance of compressor and turbine stages is influenced by complex unsteady phenomena related to secondary flows, wake interactions, and oblique shock waves. In high-pressure turbines, these interactions become even more critical due to the transonic nature of the flow and the high blade loading. Moreover, the flow exiting the combustion chamber, characterized by high temperatures and tangential non-uniformities, can induce unsteady effects that impact blade cooling and lifespan. Finally, the stationary and rotating components of turbine stages are subjected to severe thermo-mechanical stresses, requiring the integration of advanced cooling systems to prevent component failure.

To describe the various cooling systems available today in most engines, we con-sider the common blade construction scheme, illustrated in the following figure:

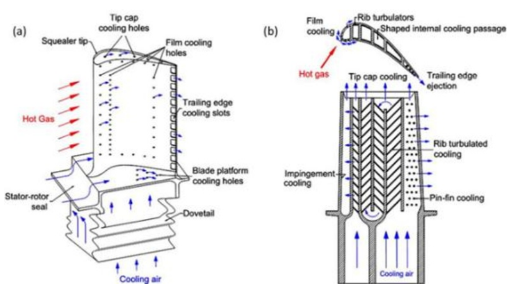

Fig. 2. Overview of turbine blade cooling methods illustrated schematically: (a) external cooling and (b) internal cooling [7]

The starting point is a blade root equipped with an inlet channel that supplies the blades cooling systems with relatively cold air extracted from the compressor. This cooling air then flows through one or more cooling channels before ultimately being discharged into the turbine main flow. Two types of cooling can be used, depending on whether the cooling airflow primarily interacts with the external or internal surfaces of the blade.

4 Material technologies

Since the 1960s, single-crystal casting and high-performance alloys have replaced traditional forging, revolutionizing the thermal and mechanical efficiency of turbine blades. Third-generation materials such as René N6 and CMSX-10 have raised the operating temperature of this technology while reinforcing its material, making the technology a building block for the future, believes Rolls-Royce. In addition, the low weight and excellent thermal and chemical resistance characteristics of ceramic matrix composites (CMC) are turning them into a viable alternative for superalloys. Their susceptibility to oxidation limits their application. Finally, thermal barrier coatings (TBC) sheathing is critical in reducing the temperature of blades by approximately 150 K, thereby enhancing energy efficiency with reduced fuel consumption. The coatings are also potential in providing enhanced durability and resistance. [5]

Liuxi Cai et al. [2] investigated the thermal degradation of turbine blades subject-ed to extreme operating environments, accounting for factors such as centrifugal forces, aerodynamic loading, and elevated temperatures. Focusing on the first-stage rotating blade under typical service conditions, they employed a coupled thermal–fluid–structural simulation using finite element methods. Their study analyzed the influence of the internal cooling configuration and the thickness of the thermal barrier coating (TBC) on the resulting temperature distribution and induced thermal stress-es within the blade material. The result illustrates that the fields of temperatures are extremely non-homogeneous and generate huge thermal stresses which show direct relationship to such temperature contrasts. In particular, they demonstrated that thickening the TBC indeed reduces the peak temperature and interior and surface thermal gradient and therefore reduces local thermal stresses and increases component life, as illustrated in Figure 3:

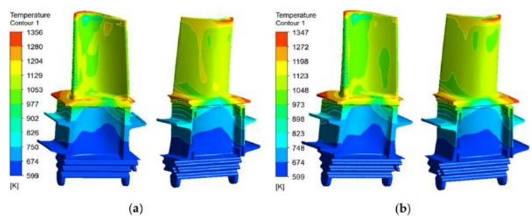

Fig. 3. Contours of surface temperature on the improved blade for varying TBC thicknesses: (a) 0.35 mm; (b) 0.5 mm [2].

Amith Shetty K and al. [8] used a systematic approach to analyze the effect of thermal insulators on the temperature distribution of a gas turbine blade. They first examined an uncoated blade, then tested different materials, including yttria-stabilized zirconia (YSZ) and lanthanum zirconate ($La_2Zr_2O_7$). Their results show that YSZ reduces the maximum blade temperature by 18%, while $La_2Zr_2O_7$ provides an even greater reduction of 19.5%, confirming its superior effectiveness as a thermal barrier. This study highlights the importance of TBCs in enhancing the durability and performance of turbine blades under extreme conditions.

5 Cooling technologies

5.1 Internal cooling

Internal cooling is the oldest technique of cooling used in turbine blades. Internal cooling is the technique of passing cooling air through channels that are designed within the blade. Over time, the technique has evolved into more sophisticated systems, such as multi-pass systems, which have features like fins, turbulators, or pins. The features are intended to create a thermal pumping effect and enhance heat transfer by augmenting turbulence within the channels. This evolution has optimized cooling efficiency while meeting modern applications rising demands.

Due to its unique structure, the U-shaped channel in turbine blades plays a very crucial role in blade cooling. Optimization of its structure primarily focuses on optimizing the channel's shape and size.

Md Redwan Iqbal et al. [9] studied the internal cooling of turbine blades by pro-posing various configurations of circular cooling holes distributed along the blade span, with 4, 6, and 8 holes arranged in both inline and staggered patterns. Their study revealed that using a staggered configuration and increasing the number of holes effectively reduces the surface temperature.

Qilong Liu et al. [10] proposed a new helical cooling structure of U-shaped channels with different rotational speeds. The study revealed that the structure has the capability to homogenize the flow, reduce low heat transfer regions, and increase the Nusselt number by up to 37%, while limiting the increase in flow resistance to 11.6%. This significantly enhances the cooling performance of turbines.

Seungchan Baek et al. [11] examined the relationship between three-dimensional flow structure and surface heat transfer in an actual internal cooling channel of the trailing edge of a turbine blade, as shown in the following figure:

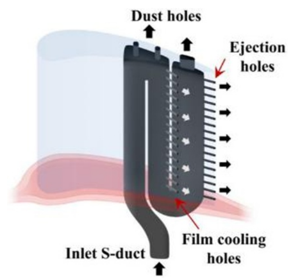

Fig. 4. Surface temperature Geometrical schematic for internal cooling serpentine channel within trailing edge [11]

The first S-shaped passage enhances heat transfer upstream of the first ribbed passage due to an intense pair of vortices, as well as additional friction caused by secondary flow. In the second passage, the film cooling holes ensure that the separation bubble attaches only to the suction side and create a high axial velocity region around the holes by directing the surrounding flow toward the hole periphery. This effect also occurs near the ejection holes in the third passage.

Nowak and Wróblewski. [7] studied the internal cooling mechanism of a C3X blade by setting the number of internal passages to 10. They varied geometric parameters, such as the diameter and location of the holes, to optimize cooling efficiency. Their results show that these adjustments effectively reduce the wall temperature and improve the thermal management of the blade.

5.2 Impingement and/or effusive cooling

The leading edges of turbine blades undergo severe thermo-mechanical and aero-dynamic loading and therefore need advanced cooling technologies to make them structurally durable. Of all, the most favourable method that has been introduced into practical use is impingement cooling (IC) introduced by Chupp et al. (1960), an additive can be applicable by increasing the heat transfer but also by being adapted to the hornsital shape of a turbine blade [12]. A development along these lines has resulted in the impingement/effusion or double-wall cooling. This approach consists of an impingement plate and an effusion plate (Figure 5):

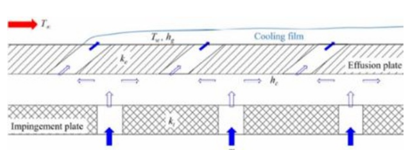

Fig. 5. Representation of the double-wall cooling system layout [6]

The double wall cooling concept operates through a multi-stage process. Initially, coolant is introduced via impingement holes, where it strikes the inner surface of the effusion plate, promoting intense heat transfer. It then flows through the internal channel formed between the two walls, continuing to absorb thermal energy. Finally, the fluid exits through effusion holes, creating a protective film that thermally shields the external surface of the effusion plate from the high-temperature turbine gases. The main objective of this configuration is to maximize internal heat extraction be-fore the coolant is expelled as a film layer. Research has highlighted that both the layout of the impingement and effusion holes, as well as the cooling mass flow rate, are critical parameters for optimizing system performance. Additionally, incorporating advanced hole designs such as staggered or helical arrangements can further enhance thermal efficiency with minimal impact on flow resistance.

A major limitation of this cooling technique lies in the interference caused by up-stream jets, which displace the coolant emerging from downstream impingement holes away from the target surface. This interaction contributes to the thickening of the thermal boundary layer, thereby reducing the overall cooling effectiveness. Moreover, as the number of impingement holes increases, this decline in performance becomes more pronounced. To address these issues, researchers have proposed several alternative configurations aimed at enhancing cooling efficiency:

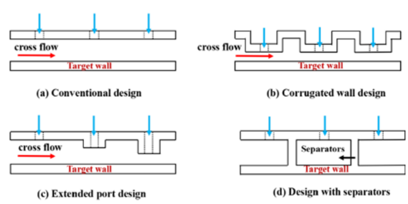

Fig. 6. Comparison of impingement cooling schemes developed to limit crossflow impact [12]

Recently, Wu and al. [12] studied the impingement cooling of a turbine blade leading edge and tested two configurations: impingement cooling with and without separators. They found that the addition of separators reduces the effect of crossflow, increases the heat exchange surface, and thins the boundary layer, significantly im-proving cooling efficiency. This modification resulted in a temperature reduction of 32.2 K compared to the traditional model without separators.

Jinfu Chen et al. [13] conducted an investigation into thermal regulation methods for the leading edges of turbine blades. Their work, depicted in Figure 7, assessed the performance of several advanced internal cooling strategies, including vortex based cooling, impingement techniques, and double impingement configurations.

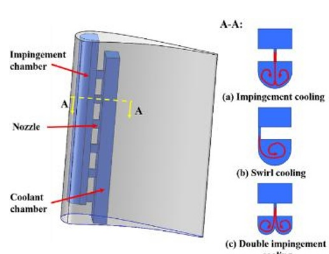

Fig. 7. Comparison of internal cooling methods at the blade leading edge: (a) IC, (b) SC, and (c) DIC [13].

They optimized two cooling strategies using a multi-objective genetic algorithm (MOGA). The optimized structures expand the area with a high Nusselt number and ensure a more uniform heat transfer distribution (see figure 4.5). Compared to vortex cooling, these optimized strategies improve heat transfer by 7.5% to 15.5% and re-duce friction losses by 6.7% to 0.5% for a Reynolds number of 18,500. These improvements contribute to an overall increase in aero-thermal efficiency of at least 15.8%.

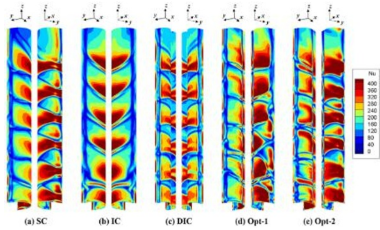

Fig. 8. Nu distributions on the target wall of the five cooling models at Re = 18500 [13].

5.3 External cooling

The objective of this mechanism is to form a protective air layer to overcome the aero-thermal constraints experienced by the turbine blade, particularly in critical are-as.

It is important to note that the blade edges are critical zones, especially the leading edge, which is subjected to extremely high thermal loads due to its direct exposure to the hot gas flow. For this reason, developing effective cooling methods is essential, with film cooling proving to be particularly effective for this region. Typically, this cooling is achieved through multiple rows of cooling fluid injection holes, spaced more closely together than other film cooling holes on the blade. On the other hand, the trailing edge, although less exposed to intense thermal constraints, can experience deformations primarily due to its thinner design and less robust structure. These de-formations are often associated with fatigue phenomena or residual aerodynamic stresses.

Meng Gu et al. [14] studied four cases under rotational conditions:

Case A: The impact of changing leading edge wall thickness on film cooling using L/d ratio is studied with wall thicknesses of 1,2 and 3 mm

Case B: The number of holes and the amount of each holes diameter is modified independently.

Case C: Hole size and count are modified in tandem to preserve the same inter-hole spacing

Case D: The number of holes and their size are changed in such a way that the to-tal outlet area of the holes remains unchanged.

As results, they found that:

Case A: The film cooling performance is consistently influenced by both the num-ber of holes (N = 10 or 13) and the hole diameter (d = 0.64 mm or 0.75 mm), with a clear monotonic relationship observed across all blowing ratios.

Case B: The film cooling performance is consistently influenced by both the num-ber of holes (N = 10 or 13) and the hole diameter (d = 0.64 mm or 0.75 mm), with a clear monotonic relationship observed across all blowing ratios.

Case C: When the ratio between hole spacing and diameter is fixed at the leading edge, the film cooling effectiveness still varies notably depending on both the number of holes (N = 7, 9, 11, 13) and their diameters, even under a constant blowing ratio. In particular, using only 7 holes with an increased coolant mass flow does not enhance the cooling performance, as it intensifies the interaction between the coolant jet and the mainstream flow. Conversely, configurations with a moderate number of holes (N = 9 or 11) achieve better coverage and deliver improved thermal protection at the leading edge (see Figure 9).

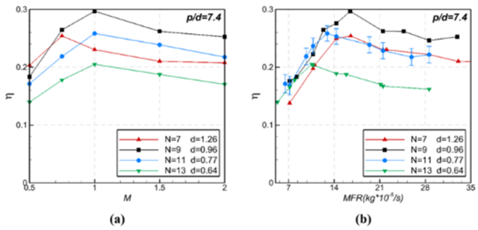

Fig. 9. Influence of blowing ratio (a) and mass flow rate (b) on film cooling performance, averaged over the surface area, for all cases where p/d = 7.4 [14].

Case D: When the total exit area of the film cooling holes is maintained constant at the leading edge, changes in the number and diameter of holes have minimal effect on overall cooling efficiency except for the configuration with the lowest number of holes (N = 7), which shows reduced performance. Increasing the number of holes, especially up to N = 13, results in a more uniform distribution of the coolant film across the surface.

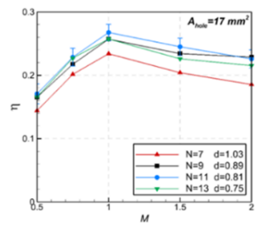

Fig. 10. Relationship between blowing ratio and area-averaged cooling effectiveness at a fixed hole area ratio [14].

Cunliang Liu et al. [15] studied cooling efficiency for two turbine blades: a reference blade and an improved blade, by varying turbulence intensity and mass flow ratio, using the Pressure Sensitive Paint (PSP) method. Both blades have an identical distribution of hole positions, but the hole shapes differ: the reference blade features cylindrical holes, while the improved blade has fan-shaped holes inclined on the suction and pressure surfaces. Both configurations include five rows of cylindrical holes at the leading edge and four rows of cooling holes on the suction and pressure surfaces (see Figure 11).

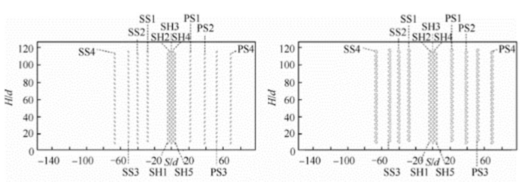

Fig. 11. Unfolded picture of the film hole positions on the blade surface [15]

The findings indicate that the enhanced blade achieves noticeably greater film cooling effectiveness than the baseline design. Nonetheless, higher turbulence intensity leads to a decline in cooling performance along the blade surface an effect that becomes less pronounced with increasing mass flow ratio. Furthermore, at low mass flow ratios, shaped cooling holes exhibit greater sensitivity to turbulence intensity compared to configurations with multiple rows of cylindrical holes.

Tianyi Sun et al. [1] carried out a comprehensive sensitivity analysis on the aero-thermal behavior and cooling performance of turbine blades, taking into account the impact of residual vortices from the combustion chamber as well as localized hot spots. Their results revealed that the direction of the vortex affects both the total pressure loss and the uniformity of the thermal field within the turbine stage. In particular, a positive vortex—rotating in the same direction as the rotor enhances blade vortex interaction, leading to a 30% increase in aerothermal variability compared to a negative vortex. On the other hand, this same configuration results in a 37% reduction in the average sensitivity of the heat transfer coefficient, suggesting improved thermal stability.

Clogging of film cooling holes poses a significant challenge, as it elevates thermal loads and undermines the effectiveness of the cooling process, ultimately reducing the thermal protection of turbine blades. In their study, Kewen Xu et al. [16] focused on this phenomenon at the squealer tip, examining how clogging influences flow behavior, film cooling efficiency, and heat transfer characteristics. By adjusting parameters such as clogging rate, clogging angle, and blowing ratio, they observed that high-er levels of clogging disrupt the ejection dynamics of the coolant. This results in an increase in both jet velocity and incidence angle, which in turn causes the cooling vortex to detach from the cavity region leading to a marked drop in cooling efficiency. Notably, for blowing ratios of 0.5 and 1.0, the film cooling effectiveness declined by 32.11% and 39.40%, respectively, when the clogging rate reached 0.6 and the clogging angle was 40° (refer to Figure 12). Moreover, elevated clogging rates were associated with increased heat transfer coefficients, thereby exacerbating the thermal stress experienced at the squealer tip.

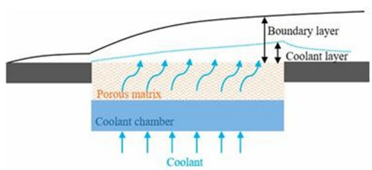

Fig. 13. Schéma de principe du refroidissement par Transpiration [17]

This This approach promotes a uniform distribution of the coolant within the structure, thanks to the large internal volume and high specific surface area characteristic of porous materials, which enhance heat transfer efficiency. By decoupling the cooling structure from the component's load-bearing framework, this method not only ensures effective and reusable thermal protection but also contributes to im-proved mechanical resilience under thermal stress. Liu et al. [6] investigated sintered porous materials with varying solid-phase thermal conductivities. Their findings revealed that although the thermal performance difference between porous bronze and porous stainless-steel plates was minimal, the bronze material resulted in a more even temperature profile (Figure 14a). Furthermore, the study confirmed that even a limited flow of cooling fluid could offer substantial thermal shielding, and that increasing the coolant injection rate improved overall cooling effectiveness (Figure 14b).

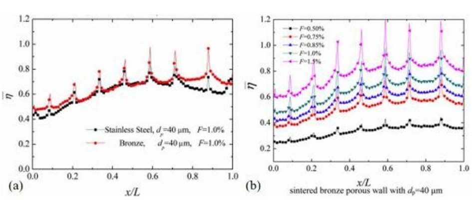

Fig. 14. Variation in transpiration cooling efficiency with respect to (a) thermal properties of the porous matrix and (b) coolant injection levels [6].

6 Parameters affecting cooling performance

According to the literature, several parameters influence the cooling performance of turbine blades. Among them, geometric parameters such as the diameter, number, shape, and inclination angle of the cooling holes play a crucial role. Additionally, other factors, including mass flow rate, flow characteristics, and turbulence intensity, significantly impact cooling efficiency.

To establish quantitative relationships between these parameters, it is necessary to study their interactions by varying some while keeping others constant. In this section, we present the key parameters used in the literature to characterize the thermal and hydrodynamic performance of turbine blade cooling.

Reynolds number Re is defined as follows:

$$R_e = \frac{\rho u D_h}{\mu} \quad (1)$$

Where D_h is the hydraulic diameter, μ is the fluid dynamic viscosity, u is the velocity and ρ is the fluid density.

The calculation method of the convective heat-transfer coefficient

$$h = \frac{q}{\Delta T} = \frac{Nu\, K_f}{D_h} \quad (2)$$

Where K_f is thermal conductivity of fluid (W/m.k)

Nusselt number is normalized by Dittus-Boelter correlation which is used to calculate forced convective heat transfer of full developed flow in smooth channels:

$$Nu_0 = 0.023\, R_e{}^{0.8} P_r{}^{0.4} \quad (3)$$

The friction factor is defined as:

$$f = \frac{\Delta P}{\frac{1}{2}\rho u^2} \frac{D_h}{L} \quad (4)$$

where ΔP is the pressure drop between inlet and outlet of the finned channel, L is the length of the finned channel.

The air friction factor for fully developed turbulent flow in a smooth channel (f0) is defined as:

$$f_0 = 0.316 R_e{}^{-0.25} \quad (5)$$

The thermal performance factor is defined as:

$$TPE = \left(\frac{Nu}{Nu_0}\right)\left(\frac{f}{f_0}\right)^{-1/3} \quad (6)$$

The adiabatic film cooling effectiveness is defined as:

$$\eta = \frac{T_{aw} - T_\infty}{T_c - T_\infty} \quad (7)$$

where, the T_{aw} represents the temperature on the adiabatic wall. T_∞ represents the inflow temperature of the mainstream. T_c represents the inlet temperature of the coolant.

The blowing ratio is defined as:

$$M = \frac{\rho_c u_c}{\rho_\infty u_\infty} \quad (8)$$

where, ρ_c and ρ_∞ represent the densities at the coolant and main stream inlets, respectively. u_c and u_∞ represent the flow velocities of the coolant and main stream at inlet boundaries, respectively.

The temperature ratio (TR) is defined by:

$$TR = \frac{T_\infty}{T_c} \quad (9)$$

To exhibit the flow resistance behavior along the flow direction, total pressure loss coefficient (C_p) is defined in Eq. (10):

$$C_p = \frac{P_{t,in} - P_{t,Local}}{\frac{1}{2}\rho u_c^2} \quad (10)$$

Where $P_{t,in}$ is the total pressure at the coolant inlet, $P_{t,Local}$ is the averaged total pressure and u_c is the velocity magnitude at the coolant inlet.

7 Numerical simulation methods

7.1 Numerical methods

Turbulence modeling is a crucial aspect of numerical simulation in fluid mechanics. It describes the irregular and chaotic fluctuations in fluid motion across various spatial and temporal scales. Turbulent flows are prevalent in phenomena such as atmospheric currents, flows inside turbofans and turbojets, as well as aerodynamic interactions around wings. The goal of turbulence modeling is to predict statistical characteristics of these fluctuations, including mean velocity, vortices, and energy dissipation. This is achieved by solving the Navier-Stokes equations with appropriate turbulence models that account for turbulent effects on the flow.

Several approaches exist for turbulence modeling, with two-equation models, such as the K-ε and K-ω models, being the most commonly used. These models introduce two additional variables to the standard conservation equations, allowing for the calculation of turbulent viscosity and turbulence production.

More advanced methods, such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS), provide higher-resolution insights by directly resolving large-scale turbulent structures without relying on turbulence models for small-scale effects. These techniques are particularly useful for high-fidelity simulations where small-scale turbulence plays a significant role.

7.2 Turbulence model

The transition from a continuous problem described by partial differential equations to a discrete problem relies on traditional numerical analysis methods. Three main approaches are used to discretize a continuous problem: the finite difference method (FDM), the finite element method (FEM), and the finite volume method (FVM). In widely used CFD software such as OpenFOAM, ANSYS Fluent, and Star-CCM+, the Finite Volume Method (FVM) is commonly applied to solve the governing equations. This method relies on a block-based approximation approach, involving two main steps: the discretization of the computational domain and the governing equations

When deriving discrete equations, a crucial step is interpolating physical quantities and their derivatives at the control volume interfaces based on nodal values. Different interpolation methods, known as discretization schemes, lead to different discrete results. Among the commonly used schemes in wind and sand simulation problems are the central difference scheme, the second-order upwind scheme, and the QUICK scheme (Quadratic Upstream Interpolation for Convective Kinematics).

Central difference is a linear interpolation technique commonly used to discretize the diffusion terms. However, this scheme is not appropriate to discretize the convection term,

because there is no accounting of the preferred direction of convection. The upwind scheme on the other hand takes into account the direction of the flow and gives a physically realistic solution, even for coarse meshes, but it is limited by numerical diffusion. The QUICK scheme, as a higher order discretization meth-od, is known to be particularly excellent in representing the flow field gradients, especially in convection-dominated conditions. [18]
Regarding solution techniques, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is the most widely used. Additionally, improved algorithms such as SIMPLEC (SIMPLE-Consistent) and PISO (Pressure-Implicit with Splitting of Operators) are also employed in current research to enhance the accuracy and efficiency of simulations.

7.3 General transport equation

The governing equations of fluid mechanics form a set of mathematical equations that describe the behavior of fluids. These equations are fundamental for understanding and predicting fluid motion in various contexts. We will use a general equation from which we will derive the following equations: continuity, Navier-Stokes (NS), and energy. [19]

Using a general variable ϕ, the conservative form of all CFD equations can be conveniently written as follows:

$$\frac{\partial(\rho\phi)}{\partial t} + \vec{\nabla}.\left(\rho\vec{V}\phi\right) = \vec{\nabla}.\left(\Gamma\vec{\nabla}\phi\right) + S_\phi \qquad (11)$$

To write the continuity equation, the following substitutions must be made:

$$\phi = 1, \qquad \Gamma = 0 \text{ and } S_\phi = 0$$

For Navier-Stokes (N.S.), it must be:

$$\phi = \vec{V}, \qquad \Gamma = \mu \text{ and } S_\phi = -\vec{\nabla}P + \rho\vec{g}$$

For energy, it must be:

$$\phi = C_pT, \qquad \Gamma = \frac{K}{C_p} \text{ and } S_\phi = \phi + \dot{q}$$

8 Conclusion

This article provides a comprehensive overview of the advancements in cooling techniques applied to gas turbine blades. It begins by introducing the historical con-text of blade cooling, tracing the evolution of turbine inlet temperature (TIT), and addressing current challenges in gas turbines. Various cooling methods, including convection cooling, film cooling, impingement/effusion cooling, and transpiration cooling, are thoroughly examined based on the latest research. These techniques can be broadly categorized into two main approaches: internal and external cooling.

Internal cooling efficiency can be enhanced through several methods, such as jet impingement cooling, pin-fin cooling (primarily used at the trailing edge), and internal passages equipped with turbulence-enhancing structures like turbulators and ribs, which have been extensively studied. Despite technological advancements, film cooling remains a widely adopted solution due to its effectiveness in mitigating aerothermal constraints by creating a protective air layer that shields the blade from high-temperature gases. Therefore, further optimization of film cooling is recommended, focusing on refining geometric and fluidic parameters to enhance its efficiency and overall performance

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