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Advancements in Gas Turbine Blade Technology: Cooling Strategies, Materials, and Failure Mechanisms

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1. INTRODUCTION

The International Energy Agency (IEA) projects that, from 2000 to 2030, the world's total energy demand roughly two-thirds of what it is now will rise by 1.7% year. In order to use sustainable fuels, modern turbo-machinery needs to have high specific power outputs, improved electrical efficiency in power generation, cheap investment costs, low pollution emissions, and low maintenance and operating expenses. Since the markets for power distribution in the power industry have been expanding in many nations, independent power providers are becoming more and more competitive. Flexible power plants with improved production efficiencies are able to meet the fluctuating power demands. It is possible to attain about 60% efficiency by implementing various cooling techniques.

The most efficient large-scale power generation system available today is the combined cycle gas turbine (CCGT). It can reduce CO2 emissions to about one-third of those from coal-fired plants and has a thermal efficiency of 64% (LHV), which is about 40% more efficient than coal-fired power generation. But even CCGTs will require additional advancements and modifications before they can become a significant power production source and become carbon neutral by 2050.

1.1 Internal cooling in turbine blades

Gas turbine engine turbine airfoils are internally cooled using methods such rib turbulators, pin fins, dimpled surfaces, swirl chambers, and surface roughness to increase convective heat transfer rates. [1]. Ligrani et al. [1] state that all of these devices work to raise turbulence levels and secondary flows in order to improve mixing and, in certain situations, to create coherent fluid motions that take the shape of vortices that are orientated streamwise. In addition to enhancing secondary heat advection away from surfaces, these vortices and secondary flows also increase the generation of three-dimensional turbulence by increasing shear and generating velocity gradients over significant flow volumes.

Because of this, a larger portion of the flow fields experience turbulence transfer. All of these technologies improve heat transmission in one way or another by increasing the surface areas that may be heated by convection. Optimal thermal protection with minimum coolant air consumption, pressure drop penalties in coolant tubes, and mass flow rates of coolant is the end aim of these internal cooling systems. Adequate thermal protection is indicated by sufficiently low absolute temperatures and reasonably uniform temperature distributions, which are characterized by sufficiently mild temperature gradients inside solid components. Figure 1 from Han et al. shows the usual internal cooling design of a multi-pass turbine blade. [2, 3].

In this configuration, the airfoil's cooling air enters through the blade root and travels down one of multiple interior passageways. The cooling passageways at numerous sites are often constricted due to the blade form, making it challenging to cool. Because these cooling tunnels have to match the external turbine airfoil curves, they also typically adopt complex cross-sectional geometries.

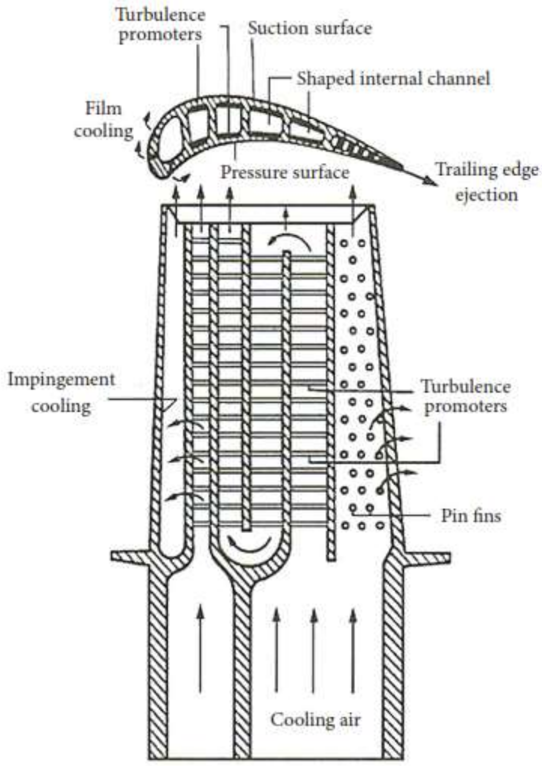

Figure 0.1 Typical Internal Cooling Arrangement [1]

As a result, the present trend in turbine components has advanced. Designing for cooling entails working on both internal and exterior thermal protection systems, including film cooling, at the same time. Considerations for neighbouring conjugate conduction changes in adjacent solid components and related aerodynamic pressure loss penalty concerns are made. Designers, producers, and researchers have devised internal cooling solutions that employ many device combinations inside a single coolant path in an effort to fulfil these various needs. A number of studies have combined rib turbulators, pin fins, and dimples; for example, Murata et al. [4] and Rao et al. [5] both use rib turbulators and pin fins together, while Siw et al. [6] use rib turbulators and pin fins together, all within the same coolant flow.

1.2 Blade material and geometrical construction

The primary component of a gas turbine, the blades are in charge of transforming the thermal energy of a compressed gas at a high temperature into mechanical power. Recent research has demonstrated that high temperatures, frequent vibrations, wear and tear, and coating. The main causes of gas turbine blade failures are erosion and tension that results in deformations. Turbine blade failure accounts for as much as 42% of gas turbine failures [8]. Gas turbine blades in power generation systems are subjected to high temperatures and pressures, as well as significant fatigue loads and mechanical stresses, all of which have an impact on the blades' performance [9]. In order to maximize turbine performance and reduce failures, a great deal of research has been done to examine these reasons of failure and determine the best materials for blade manufacturing.

In order to find appropriate blade materials for open cycle industrial gas turbines, Salwan et al. examined a variety of materials and their compositions. They came to the conclusion that alloys such CMSX2, CM 247 LC, Mar M247, PWA 148, and CM 247 LC were the best choices for blade constructions [8]. In order to examine the impacts of five distinct materials on the geometry of a gas turbine blade, Chintala et al. [10] employed the Reverse Engineering (RE) process to study a gas turbine blade under steady loading circumstances of three types of loads: axial, tangential, and centrifugal. According to the data, the main factor causing blade failure is centrifugal forces, and titanium is the most practical and secure material to employ when designing blades under severe fatigue loads, thermal stresses, and centrifugal loads. Martelli et al. looked into the ideal operating conditions for gas turbines used in combined cycle power generation on a big scale [11]. When building blades, Ceramic Matrix Composites (CMCs) were used to ensure adequate chemical and thermal resistance as well as to calculate the optimal pressure ratio and turbine inlet temperature (TIT). According to their findings, pressure ratios above 60 led to an increase in power production of up to 66%–110% at TITs of 2000 ◦C and 2200 ◦C at acceptable blade temperatures of 1300 ◦C and 1500 ◦C, respectively [12]. In order to prevent failure, gas turbines today must be repaired and restored due to fatigue, cracks, and blade damage caused by rising operating temperatures. According to Gabrielli et al., the laser metal deposition approach is the best technology for restoring blades while preserving the material's integrity and improved thermal resistance. [13]

2. LITERATURE REVIEW

To begin, this literature review has organized all of the works into several groups according to how they contribute to the growth and improvement of gas turbine research and technology. Next, a few research issues are covered under each section, along with a selection of pertinent literature. The results of these literature reviews are then compared to a few common fields and systematically presented in tabular form. This review is narrative in nature, as it thoroughly examines multiple reasons and aspects that contribute to the proper operation of gas turbines, rather than focusing on a particular problem statement. Priority was given to research involving gas turbine applications for power generation above applications in airplane propulsion when searching for pertinent articles. After extensive searching of well-known databases such as Science Direct, IEEE explore, Springer, the Directory of Open Access Journals (DOAJ), etc., 106 publications were selected for inclusion in this review. A few chosen quantitative studies are included in this review article; however the most of the research is qualitative. The majority of the times, thorough reviews are carried out, and the remaining articles are thoroughly examined and recorded for comparison.

2.1 Blade material and geometrical construction

In order to ascertain the ideal thickness of Thermal Barrier Coating (TBC) using Partially Stabilized Zirconia (PSZ) for thermal and stress analysis at various TBC thicknesses ranging from 100 to 800 μm [51] of two materials, Sankar et al. [50] created a 3D model of the gas turbine blades used for large-scale power generation [52, 53]. Up until a certain point, when a further rise in TBC thickness resulted in an increase in heat flux and temperature, the temperature and heat flux reduced as thickness grew [54, 55]. After normalizing the data for a thickness of 550 μm [56], three characteristics were taken into consideration: heat flux, temperature, and cost [57, 58]. The results showed that Inconel 718 was better suited for blade construction at the blade root, with greater stress values [59].

Shin et al. looked into the propulsion and power-generating efficiency and resistance of TBCs turbine engines. They examined a plasma-sprayed TBC made of 7 weight percent Yttria stabilized Zirconia (PS 7YSZ), evaluated them at different gas temperatures, particle impact velocities, and impingement angles, and compared the outcomes to that of an electron-beam physical vapor deposition TBC (EB-PVD 7YSZ). At the University of Cincinnati's GT Erosion Lab, the analysis and erosion rates were calculated using alumina particles in the following temperature ranges: 540 - 982 ◦C, 20 - 90◦ angle, and velocity ranges of 122 - 305 m/s. According to the findings, erosion rates increase with gas temperature and velocity, with EB-PVD 7YSZ blades eroding 10 times less quickly than (P S7YSZ)[60]. Nguyen et al. examined Ytterbium Silicate-Based Nanocomposite Yb2Si2O7/Yb2SiO5 as the best coating for multilayered environmental barrier coatings (EBCs) for the gas turbine blades built of Silicon carbide (SiC) ceramic in order to increase blade performance of large-scale aero derivative engines [61]. They stated that the nano composites showed self-healing capabilities for cracks in the blades caused by heat stress. They evaluated the regeneration of Yb2SiO5 utilizing water vapor heat treatment in an effort to preserve and enhance its self-healing efficiency, and the results demonstrated a notable improvement in its capacity to repair cracks (3–30%)[62].

By evaluating stress, vibration, temperature, cost, and physical characteristics, Singh et al. [63] evaluated four alternative materials for the manufacture of gas turbine blades and found that Nimonic 80A was the most practical material. With a fixed blade root and a load applied to the blade tip, structural and stress evaluations were conducted on the blades; Nimonic 80A showed the least amount of deformation. Modal analysis is used to assess the impacts of vibration by calculating the natural frequencies for each material's numerous modes [64, 65].and the greatest range for modal frequency was Nimonic 80A. Subbarao et al. conducted a computational analysis to examine the primary causes of blade failure in small-scale gas turbine engine blades made of Nimonic alloys that are used for work output and propulsion. Along with examining blade deformation for varied TIT and pressures, they looked into various structural and thermal stresses. They determined that Nimonic-263 is superior to Nimonic-105 and Nimonic-80A for aerodynamic applications because of the frequent failure that was discovered near the blade root [66].

In order to determine the best material and blade profile for power generation, Kumar et al. [67] performed research and found that Inconel 625 at a 72.5° bent angle was the most appropriate. For the profile, they used three models: NACA 6409, NACA 6409 bent at 145° and 72.5°, respectively. For every blade material, the three different speeds of 20,000, 40,000, and 60,000 RPM were examined for every blade profile.

Table I Different cooling methods employed in gas turbine.

Literature	Type of cooling	Findings	Limitations	Applications
Fan et al. 2019	Vortex cooling (VC)	• Heat transfer intensity is high • Thermal Performance factor is high • Pressure loss is lowest.	• High pressure loss. • Heat transfer intensity is not high VC • Thermal performance factor is not high as VC.	• Designing of gas turbine using the best cooling method according to requirement
	Middle-double vortex cooling (M-DVC)	• Not suitable for cooling.	• Poor Flow.	

	Tangential-double vortex cooling (T-DVC)	• The distribution of pressure is uniform.	• Heat transfer intensity is very low and uneven.	
	Impingement cooling (IC)	• Used to determine the cooling requirement to find better efficiency.	• Deviation of the streamlines larger with increasing upwind area of nozzle.	
Matci et al. 2018	Internal Convection Cooling Film Cooling	• Suitable for any types of required operating condition, fluid properties, cooling system, and blade geometries.		
Moskalenko et al. 2016	Steam Air	• Steam coolant much more efficient than air.	• 1st stage GT rotating blades restrictive mechanisms of GT. • Maximum mechanically and thermally loaded airfoils. • Creep resistance is life-limiting factor for airfoils • Values vary from geometry to geometry	• Innovative model of GT cycle which is less time consuming. • Applicable to attain better cooling efficiency.

Furthermore, modal analysis was carried out for every profile. necessary materials to keep the turbine from resonating when it is operating [68]. In order to reduce blade failure and fatigue resulting from vibrational effects caused by the misalignment of the rotating turbine components, Ikpe et al. [69] compared two materials for the gas turbine blade in the Trans-Amadi power plant [70,71]. After comparing the two materials' fundamental frequencies to the turbine's operating frequency, they concluded that both were safe for use. However, IN738 was found to be a better choice for the first stage rotor blade material, while U500 might fail in such situation.

The effects of thermal barrier coating deterioration are illustrated in Fig. 6, along with the ideal thickness for such a protective layer to reduce failure and erosion risks. A plot of TBC coating against three parameters—temperature, heat flux, and cost—is shown in Fig. 6(a) using the normalized values of these variables to determine the ideal PSZ thickness while keeping costs within an affordable range [50]. The saturation level of the R(red) component is analyzed in Fig. 6(b) to determine the impact of operation duration on oxide layer thickness [73]. From a value of 212 to 183, the thickness of the oxide layer increases as the saturation of the R component decreases. A further decrease in its value leads to a significant reduction in the thickness of the oxide layer. Lastly, High temperatures have a substantial impact on both the thickness of the transitional layer and the surface layer of the total aluminum coating, according to Fig. 6(c), which examines the influence of temperature on the thickness of aluminum coating layers [72].

2.2 Factors leading to failure of gas turbine blades

Fatigue and severe mechanical or thermal strains that result in pits, cracks, and material deterioration are the main causes of gas turbine blade failures. Fig. 7 illustrates the causes of these fractures as well as their consequences. Because the blades are subjected to high dynamic loads and heat gradients during the power production process, crack forms are more prone to start in the blades, particularly at the leading edges [74–77]. A brief discussion of each of the variables that lead to damage to turbine blades is provided below:

2.2.1 Thermal Stress and Fatigue:

To produce electricity and increase efficiency, gas turbine blades are exposed to gasses at extremely high temperatures. Due to metallurgical limitations, this causes excessive heat stresses in the blades, which can be effectively cooled by cooling systems [78] and Thermal Barrier Coating (TBC) [79]. Internal cooling, however, causes an uneven distribution of temperature, which in turn results in alternating compressive and tensile strains, which ultimately turbine performance is lowered due to thermal fatigue, which causes deformations and the creation and spread of cracks [80].

2.2.2 Mechanical Stress and Vibrational Effects:

Turbine blade failure is the result of significant mechanical stress caused by high centrifugal force and unstable dynamic stresses. fatigue in the blades brought on by Another significant factor in turbine failures is resonance and vibrations [81]. For the safe operation of turbines, modal analysis is utilized to locate cracks and identify modes of failure brought on by structural vibrations [82].

2.2.3 Fatigue:

Fatigue failure happens in blades when the applied stresses and crack diameters exceed the fracture toughness of the material. Among the most common causes of gas turbine blade failure, it affects 42% of all generators [83]. The repeated loading that occurs throughout operation might lead to either low cycle fatigue or high cycle fatigue. The material of the blade and the cycle loads dictate the fatigue life. [76–84].

2.2.4 Creep:

The term "creep" refers to the tendency of blade materials to migrate or undergo permanent deformation when they are subjected to high loads below their yield strength. Elevated temperatures lead to increased creep, which fractures the inter-granular structure and ultimately results in creep failure [85]. Creep, which leads to blade failure, has a significant impact on the fatigue strength of the materials used to make blades [84].

2.2.5 Coating Degradation:

TBCs, which are special materials used to offer insulation and protection from extremely high or low temperatures, are used to cover turbine blades [86]. However, during operation, adverse working conditions significantly erode this protective layer, especially at the leading edges, and cause the blade to change color [73]. One of the primary causes of turbine blade deterioration is coating oxidation, which creates oxides lost by erosion [77].

2.2.6 Corrosion and Erosion:

Gas turbines utilize a variety of fuels consisting of corrosive elements such as sulfur, vanadium, lead, sodium, etc. In the case of air or saltwater contamination, these chemicals produce alkali metals that cause severe corrosion attacks on turbine blades leading to failure [87,88]. Erosion on the other hand removes material from turbine blades resulting in pitting and is caused by particles of carbon. Erosion damages the thermal barrier of blades causing thermal fatigue, and cracks that lead to failure [89].

The main consequences of these failure criteria on gas turbine blades are covered in detail in the section that follows. Additionally, recommendations for potential fixes and advancements to stop these elements in turbine blades are also mentioned. Table 2 presents a summary of significant findings, materials used, restrictions, and applications from several studies on gas turbine blades.

Through the introduction of comparatively cold air from the blade's inside to its outside, film cooling creates a barrier between the hot mainstreams and the blade surface. The performance of film cooling under common engine flow circumstances, such as Reynolds number, Mach number, combustion caused high free-stream turbulence, and unstable wake flow, is determined by the blowing ratio, density ratio, number of rows, hole size, shape, and angle from the surface. The film perforations' location in relation to the blade tip, end-wall, pressure and suction sides, and leading and trailing edges are additional considerations.

Cooling films on turbine blades have recently been the subject of an increasing amount of research. The following researchers, for instance, examined various facets of film cooling: rotor blade film cooling, linear cascade nozzle guide vane film cooling, annual cascade nozzle guide vane end-wall film cooling, modeled blade tip film cooling, and Nirmalan and Hylton (1990), Camci and Arts (1985), Harasgama and Burton (1992), Mehendale and Han (1992), and Kim et al. (1995).

The high-temperature stages of the gas turbine blades were constructed using high resistance alloys in the absence of contemporary cooling techniques. Increasing efficiency has been a recent issue in the design of gas turbines, forcing engineers to employ greater intake temperatures and higher-pressure ratios, which result in tougher working conditions (Han et al. [3]).

Consequently, using cooling is unavoidable. One typical method is extracting from the compressor, which results in a significant amount of film and internal cooling, and then crossing the flow through the cooling pathways inside the blade. When assessing such cooling systems, computational fluid dynamics, or CFD, becomes an invaluable tool. One method primarily consists of solving the internal and external flows independently, then using the results of the calculations as boundary conditions in an iterative process. These kinds of iterations are used to study the temperature distribution on the blade (Carcasci et al. [4]).

Table II Studies on various Gas turbine blade materials with their limitations and applications

Literature	Research Conclusion	Materials Assessed	Analysis Performed	Superior Material	Limitations	Applications
Chintala et al. 2014 [46]	• Centrifugal forces highest and leading cause of blade failure. • Adequate structural stability with Titanium. • Titanium most suitable material for the gas turbine blade.	Al alloy, Cast iron, Magnesium, Stainless steel, Titanium	Mechanical stress, Thermal stress, Fatigue load	Titanium	• The RE technology implemented to model the turbine not 100% accurate. • Only five materials tested to observe load effects • No experimental validation done for the observed results.	• Large scale power generation • Designing and direct manufacturing of gas turbine blades using the most suitable material. • Ensuring the minimum possibility of blade failure.
Shin et al.2016 [60]	• TBC of EB-PVD 7YSZ contributed to 10 times lower erosion. • Rates of turbine blade erosion enhanced with greater gas temperature and impact velocities at the blades.	PS 7YSZ and EB-PVD 7YSZ	Blade erosion for different temperatures, velocities and angles of particle impact	EB-PVD 7YSZ	• Only Alumina particles of 27 µm used as erosive particles. • Further analysis with more types of TBCs should be used.	• Small-scale gas turbine engines for propulsion and power output • Reduce blade failure due to erosive particles. • Provide basis for TBC research at higher gas temperatures.
Kumar et al. 2017 [67]	• Three blade profiles at different RPMs on various materials analyzed. • Inconel 625 most suited material. • Best results with 72.5◦ bent blade profile.	Nimonic 80A, Inconel 625, Super Alloy X	Static structural analysis, Blade profile, Modal analysis	Inconel 625	• Transient and CFD analysis not done for desired efficiency and power generation	• Large scale power generation • Produce required power by utilizing particular RPM. • Utilize optimum blade profile, and material for maximum performance.
Ikpe et al. 2018 [69]	• Failure due to vibration in turbine blades assessed. • IN 738 was better as a first stage rotor blade material.	IN 738 and U500	Modal Analysis	IN 738	• Various assumptions made which may not have been applicable for the gas turbine under study.	• Large scale power generation • Manufacture and operate gas turbines with less chance of failure. • Provide guidance for turbine

						maintenance to prevent failure.
Sankar et al. 2019 [50	• Optimum thickness for the Thermal Barrier Coating (TBC) of PSZ was found to be 550 µm for the gas turbine blades. • Inconel 718 was found to be more feasible as a blade material.	Inconel 718 and Titanium-T6	Stress and Thermal Analysis	Inconel 718	• Only two materials analyzed for feasibility as suitable blade material. • More temperature and heat flux plots at lesser intervals to be carried out for greater accuracy.	• Large scale power generation • Improved gas turbine performance and longer blade life span. • Enables operation at higher temperatures.
Subbarao et al. 2019 [66]	• Frequent failure was found at the blade roots. • Nimonic-263 better for aerodynamic applications. • Less deformation, thermal stress for Nimonic-90 • Nimonic-80A shows greater deformation and equivalent stress.	Nimonic-263, Nimonic-105 and Nimonic-80A.	Structural and thermal stress analysis	Nimonic-263	• Only Nimonic alloys tested for suitable blade material • Stress- strain analysis not performed for various blade configurations.	• Small scale aerodynamic propulsion and power. • Prevent failure in blade roots resulting from high pressure and temperature.
Singh et al. 2020 [63]	• Four blade materials were compared by computational analysis. • Nimonic 80A determined to be the most suitable.	INCONEL alloy 617, Titanium alloy, Rhenium, and Nimonic 80 A.	Stress analysis, Structural analysis, and Modal analysis	Nimonic 80A	• The static structural analysis between the materials is only done at 2000 RPM and 900 ◦C at a particular boundary condition with no variation.	• Large scale power generation • Enhance the life span of turbine blades. • Prevent failure of blades resulting from extreme stress load and vibrations and resonance.
Rayapati et al. 2020 [92]	• Failure analysis conducted based on deformation and corresponding strain and stress • Mar-M-200 concluded to be the most suitable from a structural perspective.	IN-792, Udimet-700, Mar-M-200, Rene-41	Thermal stress, strain and stress, deformation analysis	Mar-M-200	• Only nickel-based materials analyzed so no comparisons with other alloys. • Investigation on ceramics not conducted.	• Large scale power generation • Reduce frequent failure of gas turbine blades. • Allow selection of suitable superalloy material based on nickel for the manufacture of blades of a gas turbine.

Using the Shear Stress Tensor (SST) k-ω turbulence model, Zhao Liu et al. [6] carried out a numerical solution to simulate the impact of the film hole geometries on the internal heat transfer and the external film cooling effectiveness. In light of its simulation accuracy, they came to the conclusion that the (SST) k-ω turbulence model is among the best for the numerical analysis of the impingement and film composite cooling. A few decades ago, studies were conducted to investigate the effects of various cooling techniques, including internal and film cooling, on the efficiency of gas blade turbines [7–13].

Numerous specialized hole designs have been provided in order to increase the efficiency of film cooling [14–19]. The most useful structures are fan-shaped holes, which have outstanding properties in terms of cooling effectiveness, geometry sensitivity, and flow sensitivity [20].

C3X and MARK II blades were the subject of an experimental thermofluidic study by Hylton et al. [21]. The data from the study is frequently used as a benchmark to verify the accuracy of the numerical simulations. Three blades that are linearly oriented have thermocouples installed in their curved surfaces. Cooling holes were made into the side portions of the experimental foils. We repositioned the perforations and changed the air mass flow rate to keep the foil's surface temperature constant. Lastly, the temperature distribution inside the blades was tracked in order to determine the surface heat transfer coefficient on the foils. From these kinds of studies, a few actual relationships were also taken.

Bohn et al. [22] carried out one of the earliest studies inside the CHT. They concentrated on the two-dimensional heat transfer field of the MARK II vane. They applied the boundary conditions to the holes using the empirical coefficients. Additionally, they employed the zero-equation turbulence model, which produced numerical and experimental results with a maximum error of only 2%. The surface temperature measurements and the 2D results, however, show a clear disparity. Particularly on the suction side, the anticipated temperature is higher than the actual temperature.

Heidmann et al. [23] used a different strategy to investigate a viable film cooling method for the gas turbine vane. The associated fluid-thermal problem served as the basis for their inquiry. To model metal conduction, they combined the Boundary Element approach (BEM) with the Glenn-HT approach. It was shown that thermal conduction from the outside wall to the plenum typically results in lower outside wall temperatures in conjugate heat transfer scenarios. Han et al. [24] produced 2D and 3D codes using the CHT approach. Additionally discussed was the examination of heat transport in a gas turbine's radial cooling vane. They determined that HTC would be a useful tool for assessing such systems after applying it to the surfaces of the internal cooling channels while enforcing the coolant bulk temperature as boundary conditions.

Facchini et al. [25] solved the CHT for the C3X vane using STAR-CD.

By contrasting and comparing their findings with the numerical results previously obtained by other investigations and the Hylton et al. [21] study, they further demonstrated the validity of their investigation. In that work, the projected heat transfer coefficients in all three models (K-ε turbulence with low Reynolds, K-ε RNG, and K-ε with high Reynolds) fared better than the actual data. As a result, the heat convection coefficient over the vane surface is greater than the experimental value.

Esfahanian et al. [26] used the CHT technique and Fluent software to simulate the C3X vane. They contrasted and compared two distinct turbulence intensities in many turbulence models. For validation, researchers also consulted Dees et al.'s work [27]. They discovered that the V2F model was more effective at forecasting the heat transfer coefficient across the blade when there was no turbulence.

Jang Luo et al. [28] examined the CHT of the C3X vane using the V2F turbulence model. Hylton et al. [21] discovered that these findings were confirmed by contrasting the numerical solution results with NASA's C3X experimental data. When it came to forecasting metal temperature and both internal and external heat transfer coefficients, V2F was the most accurate.

York and Leylek [5,29] used the CHT approach in their study of the C3X vane. Using an unstructured superblock mesh, three turbulence models were combined using a conventional k-ε model [5], a novel transition-sensitive eddy-viscosity model [29], and a realizable form of the same model [5,29]. After that, they compared the models to each other. The transition-sensitive eddy viscosity model produced the most accurate findings overall, suggesting that the k-ε model was more dependable than the "realizable" k-ε model.

Kusterer et al. [30] used CHT to mimic gas turbine blades with internal helical perforations. The outcomes were in good agreement with the experimental data when film cooling was applied to the blades' suction and pressure sides. The SST (k-ϋ) turbulence approach was used.

Weihong Zhang et al. [31] optimized the dimensions, locations, and forms of the C3X vane coolant channels. Using a thorough CHT technique, they also looked into the 3D model's temperature distribution and discovered the ideal shape for a 50 K temperature drop without sacrificing mechanical strength.

Rigby and Lepicovsky [32] investigated the temperature distribution data and heat transfer coefficient (HTC) from an internally cooled flat plate using both experimental work and conjugated-based numerical modeling. The experimental correlations were found to be in good agreement with the numerical calculations.

Chmielniak et al. [33] conducted a two-dimensional heat transfer research in a gas turbine that employs radial cooling, assuming bulk temperature and HTC. We employed a hybrid approach that combined an external flow simulator with the Finite Element Method (FEM) to describe the conduction process in materials. Predictions for the transition zone continue to vary, though.

Using revolving cooling channels with rib turbulators and a tip turning point running at various angular speeds, Andrew F. Chen et al. [34] examined heat transmission. Their calculations suggested that the channel had a tip-turn angle of 180 degrees and an aspect ratio of 2:1. They demonstrated that raising the vane's angular speed might triple the heat transfer ratio.

The internal cooling route of a rib-roughened gas turbine blade was examined by Toshihiko et al. [35]. They investigated heat transmission and friction in rib-roughened coolant channels using correlations derived from Takashi and Watanabe's large eddy simulation of ribbed channels [36]. They demonstrated that the ribs can be used to increase the ribbed channel's local heat transfer efficiency and that there is a good agreement between the experimental and computational results for the heat transfer ideas.

The effects of several factors on heat transfer in mini-channel heat sinks, such as mass flux, grooved passages with varying rib arrangements, phase change materials (PCMs), increasing the heat transfer surface, internally forced convection cooling, and friction characteristics, have been investigated by numerous researchers using both numerical and experimental methods [37–43]. They concentrated on the effects of the phase change material and the rib and fin designs on heat transmission and pressure drop in the well-established field of uniform channels. These experiments show that, in comparison to their unfinned counterparts, finned channels greatly enhance heat transport.

Adnan Qayoum et al. [44] examined the impact on heat transfer in a square cross-section channel flow by mixing a synthetic jet with a surface-mounted rib. The hydraulic diameter and the rib height have a ratio of 0.1625. The synthetic jet actuator was coupled to a channel with a Reynolds number of 5500 and operated at various actuation voltages and amplitude modulation frequencies. They found that, in comparison to smooth duct flow, the maximum total heat transfer increased by 132.6% at an actuation voltage of 55 V.

3. Conclusion

Gas turbine blade failure owing to inappropriate loading, mechanical vibrations, and fatigue persists despite extensive research on TBC and improvised turbine blade material. Thus, in order to further reduce failure due to mechanical and thermal cracking and corrosion, it is imperative to study the impacts of both blade material and severe stress conditions simultaneously.

It is reasonable to assume that most previous studies have not fully assessed the impact of longitudinal rib height and breadth on the cooling performance factor of blades. This is because it makes sense to assume that this phenomena has not been fully explored based on what we now know and the survey's results. Enhancement of heat transfer in gas blade turbines, decrease of coolant bulk, improvement of blade surface temperature uniformity, and reduction of thermal stress resulting from it are some possible uses of the current research's findings.

Because the NASA C3X blade is well accepted as a standard in this specific industry, we decided to use it as our ribbing test case. This means that the impacts of the blades with ribs may be shown more clearly in a test scenario without ribs. To validate the experimental data acquired by the NASA C3X turbine vane, the CHT technique is employed. The SST (k-ω) turbulence model is used in our validation procedure. These longitudinal ribs go along the cooling channels in six distinct configurations. The effects of the redesigned shape were then examined in relation to the performance factor, the mass flow rate of the channels, the heat transfer coefficient (HTC), the friction factor, and the temperature distribution on the turbine blade's surface.

In addition, it is necessary to examine novel super alloy and ceramic variations in order to improve the turbine blades' thermal durability. Additionally, rather than focusing only on first-stage failures, more study and studies should be done on turbine blade failures at higher stages. In addition to highlighting the causes and forms of failure, the solution to gas turbine unit failure should be highlighted. Finding particular fixes and suggestions for every kind of gas turbine failure should be prioritized. In addition to the tedious methods of investigation that had been used for years, such as micro-structural evaluation, visual investigation, metallographic analysis, FEM, SEM, XRD, ANSYS, and others, modern simulation, programming software, and techniques should also be used to further analyze and solve the issue related to gas turbine failures.

REFERENCES

[1] P. M. Ligrani, M. M. Oliveira, and T. Blaskovich, “Comparison of heat transfer augmentation techniques,” AIAA Journal, vol. 41, no. 3, pp. 337–362, 2003.

[2] J.C.Han, S.Dutta, and S.Ekkad, Gas Turbine Heat Transfer and Cooling Technology, Taylor and Francis, New York, NY, USA, 2000.

[3] J. C. Han, J. S. Park, and C. K. Lie, “Heat Transfer and pressure drop in blade cooling channels with turbulence promoters,” NASA CR-3837, 1984.

[4] A. Murata, S. Nishida, H. Saito, K. Iwamoto, Y. Okita, and C. Nakamata, “Heat transfer enhancement due to combination of dimples, protrusions, and ribs in narrow internal passage of gas turbine blade,” ASME Paper GT2011-45356, 2011.

[5]Y.Rao, C.Wan, Y.Xu, and S.Zang, “Local heat transfer characteristics in channels with pin fin and pin fin-dimple arrays,” ASME Paper GT2011-45449, 2011.

[6] S.C.Siw, M.K.Chyu, and M.A.Alvin, “Effects of pin detached space on heat transfer in a rib roughened channel,” ASME Paper GT2011-46078, 2011.

[7] B.A.Brigham and G.J.VanFossen, “Length to diameter ratio and row number effects in short pin fin heat transfer,” Journal of Engineering for Gas Turbines and Power,vol.106,no.1,pp. 241–245, 1984.

[8] G.K. Salwan, R. Subbarao, S. Mondal, Comparison and selection of suitable materials applicable for gas turbine blades, Mater. Today Proc. 46 (xxxx) (2021) 8864–8870, https://doi.org/10.1016/j.matpr.2021.05.003.

[9] E.A. Ogiriki, Y.G. Li, T. Nikolaidis, Prediction and analysis of impact of TBC oxidation on gas turbine creep life, in: Proceedings of the Turbo Expo: Power for Land Sea and Air 56673, 2015 p. V003T06A004.

[10] G. Chintala, P. Gudimetla, Optimum material evaluation for gas turbine blade using Reverse Engineering (RE) and FEA, Procedia Eng. 97 (2014) 1332–1340, https://doi.org/10.1016/j.proeng.2014.12.413.

[11] T. Nakamura, T. Oka, K. Imanari, K. Shinohara, M. Ishizaki, Development of CMC turbine parts for aero engines, IHI Eng. Rev. 47 (1) (2014) 29–32 [Online]. Available: https://www.ihi.co.jp/en/technology/review_library/review_en/ 2014/_cms_conf01/__icsFiles/afieldfile/2020/04/09/ 3af4d6d52f2a1d0972f2137 f87e3cd8e.pdf .

[12] E. Martelli, M. Girardi, P. Chiesa, Breaking 70% net electric combined cycle efficiency with CMC gas turbine blades, in: Proceedings of the Turbo Expo: Power for Land Sea and Air 86014, 2022 p. V004T06A012.

[13] A. Gabrielli, M. Moretto, Blades and vanes platform laser rebuilding, in: Proceedings of the Turbo Expo: Power for Land Sea and Air 84195, 2020 p. V008T18A011.

[14] Z. Wang, Z. Wang, W. Zhang, Z. Feng, Numerical study on unsteady film cooling performance of turbine rotor considering influences of inlet non-uniformities and upstream coolant, Aerosp. Sci. Thechnol. 119 (2021), 107089.

[15] I.V. Miroshnichenko, M.A. Sheremet, A.A. Mohamad, Numerical simulation of a conjugate turbulent natural convection combined with surface thermal radiation in an enclosure with a heat source, Int. J. Therm. Sci. 109 (2016) 172–181.

[16] H. Hassan, N.Y.A. Shafey, 3D study of convection-radiation heat transfer of electronic chip inside enclosure cooled by heat sink, Int. J. Therm. Sci. 159 (2021), 106585.

[17] O. Prakash, S.N. Singh, Experimental and numerical study of mixed convection with surface radiation heat transfer in an air-filled ventilated cavity, Int. J. Therm. Sci. 171 (2022), 107169.

[18] G. Su, H.-C. Chen, J.-C. Han, J.D. Heidmann, Computation of flow and heat transfer in rotating two-pass rectangular channels (AR=1:1, 1:2, and 1:4) with smooth walls by a Reynolds stress turbulence model, Int. J. Heat Mass Tran. 47 (26) (2004) 5665–5683.

[19] L. Bai, H. Deng, Z. Tao, S. Tian, L. Qiu, Rotational effects on heat transfer in a two-inlet rectangular channel roughened with pin-fins, Int. J. Heat Mass Tran. 143 (2019), 118555.

[20] J.H. Wagner, B.V. Johnson, T.J. Hajek, Heat transfer in rotating passages with smooth walls and radial outward flow, J. Turbomach. 113 (1) (1991) 42–51.

[21] S.-F. Yang, J.-C. Han, S. Azad, C.-P. Lee, Heat transfer in rotating serpentine coolant passage with ribbed walls at low Mach numbers, J. Therm. Sci. Eng. Appl. 7 (1) (2015), 011013.

[22] W.-J. Su, T.-H. Huang, Y.-H. Liu, Heat transfer and friction in trapezoidal channels with X-shaped ribs, Int. J. Therm. Sci. 164 (2021), 106871.

[23] Z. Guo, Y. Rao, Y. Li, W. Wang, Experimental and numerical investigation of turbulent flow heat transfer in a serpentine channel with multiple short ribbed passes and turning vanes, Int. J. Therm. Sci. 165 (2021), 106931.

[24] R.S. Bunker, Gas turbine heat transfer: ten remaining hot gas path challenges, J. Turbomach. 129 (2) (2006) 193–201.

[25] H.-C. Chiu, J.-H. Jang, W.-M. Yan, Mixed convection heat transfer in horizontal rectangular ducts with radiation effects, Int. J. Heat Mass Tran. 50 (15) (2007) 2874–2882.

[26] V. Sankar, P.B. Ramkumar, D. Sebastian, D. Joseph, J. Jose, A. Kurian, Optimized thermal barrier coating for gas turbine blades, Mater. Today Proc. 11 (2019) 912–919, https://doi.org/10.1016/j.matpr.2018.12.018.

[27] I.H. Shin, D.K. Lee, Y.S. Kim, J.M. Koo, C.S. Seok, T.W. Lee, Assessment of the characteristic of thermal barrier coating applied to gas turbine blade by thermo-gradient mechanical fatigue test, Procedia Eng. 55 (2013) 210–213.

[28] W. Zhu, J.W. Wang, L. Yang, Y.C. Zhou, Y.G. Wei, R.T. Wu, Modeling and simulation of the temperature and stress fields in a 3D turbine blade coated with thermal barrier coatings, Surf. Coat. Technol. 315 (2017) 443–453.

[29] S.P. Kauthalkar, Analysis of thermal stresses distribution pattern on gas turbine, Int. J. Eng. Educ. Technol. (2008) 2320–2328.

[30] E.A. Ogiriki, Y.G. Li, T. Nikolaidis, T.E. Isaiah, G. Sule, Effect of fouling, thermal barrier coating degradation and film cooling holes blockage on gas turbine engine creep life, Procedia CIRP 38 (2015) 228–233.

[31] D. Zhu, R.A. Miller, and M.A. Kuczmarski, Development and life prediction of erosion resistant turbine low conductivity thermal barrier coatings. National Aeronautics and Space Administration, Glenn Research Center, 2010.

[32] B. Li, X. Fan, D. Li, P. Jiang, Design of thermal barrier coatings thickness for gas turbine blade based on finite element analysis, Math. Probl. Eng. 2017 (2017).

[33] R.T. Marler, J.S. Arora, The weighted sum method for multi-objective optimization: new insights, Struct. Multidiscip. Optim. 41 (6) (2010) 853–862.

[34] B. Deepanraj, P. Lawrence, G. Sankaranarayanan, Theoretical analysis of gas turbine blade by finite element method, Sci. world 9 (9) (2011) 29–33.

[35] T. V, U.P. S, P.G. Reddy, C.J. Manjunath, A. Professor, Design and analysis of gas turbine blade, Int. J. Innov. Res. Sci. Eng. Technol. 3297 (6) (2007) 13533–13539 (An ISO Certif. Organ.

[36] D. Shin and A. Hamed, "Gt2016-57922 advanced high temperature erosion tunnel for testing TBC and," pp. 1–9, 2016.

[37] B. Nkoi, T.G.E. Isaiah, Advanced cycles large-scale aero-derivative gas turbines: performance comparison, J. Power Energy Eng. 4 (5) (2016) 7–19.

[38] S.T. Nguyen, et al., Recycling of a healing agent by a water-vapor treatment to enhance the self-repair ability of ytterbium silicate-based nanocomposite in multiple crack-healing test, Adv. Eng. Mater. 22 (7) (2020), https://doi.org/ 10.1002/adem.202000157.

[39] H.P. Singh, A. Rawat, A.R. Manral, P. Kumar, Computational analysis of a gas turbine blade with different materials, Mater. Today Proc. 44 (xxxx) (2021) 63–69, https://doi.org/10.1016/j.matpr.2020.06.486.

[40] A.R.S. Manral, N. Gariya, G. Bansal, H.P. Singh, P. Negi, Structural and modal analysis of chicken feather fibre (CFF) with epoxy-resin matrix composite material, Mater. today Proc. 26 (2020) 2558–2563.

[41] A.R. Manral, N. Gariya, K.C.N. Kumar, Material optimization for femur bone implants based on vibration analysis, Mater. Today Proc. 28 (2020) 2393–2399.

[42] R. Subbarao, N. Mahato, Computational analysis on the use of various nimonic alloys as gas turbine blade materials, in: Proceedings of the Gas Turbine India Conference 83532, 2019 p. V002T10A001.

[43] R.R. Kumar, K.M. Pandey, Static structural and modal analysis of gas turbine blade, IOP Conf. Ser. Mater. Sci. Eng. 225 (1) (2017), https://doi.org/10.1088/ 1757-899X/225/1/012102.

[44] A.R. Rao, B.K. Dutta, Blade vibration triggered by low load and high back pressure, Eng. Fail. Anal. 46 (2014) 40–48.

[45] A. Ikpe, Modal analysis of conventional gas turbine blade materials (Udimet 500 and IN738) for industrial applications, J. Eng. Technol. Appl. Sci. 3 (2) (2018) 119–133, https://doi.org/10.30931/jetas.452857.

[46] S.K.S. Al Adawi, G.R. Rameshkumar, Vibration diagnosis approach for industrial gas turbine and failure analysis, Curr. J. Appl. Sci. Technol. (2016) 1–9.

[47] B.A. Mohamad, A. Abdelhussien, Failure analysis of gas turbine blade using finite element analysis,, Int. J. Mech. Eng. Technol. 7 (3) (2016).

[48] M. Bogdan, J. Błachnio, J. Spychała, D. Zasada, Assessment of usability of the exploited gas turbine blade heat-resistant coatings, Eng. Fail. Anal. 105 (July) (2019) 337–346, https://doi.org/10.1016/j.engfailanal.2019.07.016.

[49] M. Bogdan, J. Błachnio, A. Kułaszka, D. Zasada, Investigation of the relationship between degradation of the coating of gas turbine blades and its surface color, Materials 14 (24) (2021) 1–21, https://doi.org/10.3390/ma14247843 (Basel).

[50] A. Semenov, S. Semenov, A. Nazarenko, L. Getsov, Computer simulation of fatigue, creep and thermal-fatigue cracks propagation in gas-turbine blades, Mater. Tehnol. 46 (3) (2012) 197–203.

[51] X. Guo, et al., Evaluation of microstructural degradation in a failed gas turbine blade due to overheating, Eng. Fail. Anal. 103 (December 2018) (2019) 308–318, https://doi.org/10.1016/j.engfailanal.2019.04.021.

[52] V. Naga, N.R. Vakada, I. Kumar, K. Prasad, N. Madhulata, Failure mechanisms in turbine blades of a gas turbine engine - an overview, Int. J. Eng. Res. Dev. 10 (8) (2014) 48–57.

[53] S. Rani, A.K. Agrawal, V. Rastogi, Failure analysis of a first stage IN738 gas turbine blade tip cracking in a thermal power plant, Case Stud. Eng. Fail. Anal. 8 (2017) 1–10, https://doi.org/10.1016/j.csefa.2016.11.002.

[54] K. Vaferi, et al., Heat transfer, thermal stress and failure analyses in a TiB2 gas turbine stator blade, Ceram. Int. 45 (15) (2019) 19331–19339, https://doi.org/ 10.1016/j.ceramint.2019.06.184.

[55] A. Szczepankowski, R. Przysowa, Thermal degradation of turbine components in a military turbofan, Eng. Fail. Anal. 134 (October 2021) (2022), 106088, https:// doi.org/10.1016/j.engfailanal.2022.106088.

[56] S. Nekahi, K. Vaferi, M. Vajdi, F. Sadegh Moghanlou, M. Shahedi Asl, M. Shokouhimehr, A numerical approach to the heat transfer and thermal stress in a gas turbine stator blade made of HfB2, Ceram. Int. 45 (18) (2019) 24060–24069, https://doi.org/10.1016/j.ceramint.2019.08.112.

[57] S. Madhavan, R. Jain, C. Sujatha, A.S. Sekhar, Vibration based damage detection of rotor blades in a gas turbine engine, Eng. Fail. Anal. 46 (2014) 26–39, https:// doi.org/10.1016/j.engfailanal.2014.07.021.

[58] S. Rani, A.K. Agrawal, V. Rastogi, Vibration analysis for detecting failure mode and crack location in first stage gas turbine blade, J. Mech. Sci. Technol. 33 (1) (2019) 1–10, https://doi.org/10.1007/s12206-018-1201-x.

[59] P. Kalapala, B.P. Anjaneya, M. Anandarao, Material Optimization and Dynamic Approach for performance criteria in application to Gas Turbine Blade to overcome resonance, Int. J. Sci. Eng. Res. 8 (6) (2017) 189–196.

[60] P. Puspitasari, A. Andoko, P. Kurniawan, Failure analysis of a gas turbine blade: a review, IOP Conf. Ser. Mater. Sci. Eng. 1034 (1) (2021), 012156, https://doi.org/ 10.1088/1757-899x/1034/1/012156.

[61] S. Kumari, D.V.V. Satyanarayana, M. Srinivas, Failure analysis of gas turbine rotor blades, Eng. Fail. Anal. 45 (2014) 234–244, https://doi.org/10.1016/j. engfailanal.2014.06.003.

[62] R. Vaßen, M.O. Jarligo, T. Steinke, D.E. Mack, D. St¨over, Overview on advanced thermal barrier coatings, Surf. Coat. Technol. 205 (4) (2010) 938–942.

[63] H. Kazempour-Liasi, A. Shafiei, Z. Lalegani, Failure analysis of first and second stage gas turbine blades, J. Fail. Anal. Prev. 19 (6) (2019) 1673–1682, https:// doi.org/10.1007/s11668-019-00764-1.

[64] Z. Huda, Metallurgical failure analysis for a blade failed in a gas-turbine engine of a power plant, Mater. Des. 30 (8) (2009) 3121–3125, https://doi.org/10.1016/j. matdes.2008.11.030.

[65] J.R. Laguna-Camacho, et al., A study of the wear damage on gas turbine blades, Eng. Fail. Anal. 61 (2016) 88–99, https://doi.org/10.1016/j. engfailanal.2015.10.002.

[66] J. Han, S. Dutta, S. Ekkad, Gas Turbine Heat Transfer and Cooling Technology'', Taylor & Francis Inc, New York, 2000.

[67] C. Carcasci, S. Zecchi, G. Oteri, "Comparison of blade cooling performance using alternative fluids," in ASME Turbo Expo, Power for Land Sea, Air 2002 (2002) 827–834.

[68] W.D. York, J.H. Leylek, "Three-dimensional conjugate heat transfer simulation of an internally-cooled gas turbine vane," in ASME Turbo Expo 2003, collocated with the, Int. Joint Power Gener. Conf. 2003 (2003) 351–360.

[69] Z. Liu, L. Ye, C. Wang, Z. Feng, Numerical simulation on impingement and film composite cooling of blade leading edge model for gas turbine, Appl. Thermal Eng. 73 (2014) 1432–1443.

[70] X. Fan, C. Du, L. Li, S. Li, Numerical simulation on effects of film hole geometry and mass flow on vortex cooling behavior for gas turbine blade leading edge, Appl. Thermal Eng. 112 (2017) 472–483.

[71] M.K. Sahu, Exergoeconomic investigation of power utility based on air film blade cooled gas turbine cycle, Appl. Thermal Eng. 122 (2017) 738–746.

[72] S.S. Baakeem, J. Orfi, H. Al-Ansary, Performance improvement of gas turbine power plants by utilizing turbine inlet air-cooling (TIAC) technologies in Riyadh, Saudi Arabia, Appl. Thermal Eng. 138 (2018) 417–432.

[73] S. Mishra, Energy and exergy analysis of air-film cooled gas turbine cycle: Effect of radiative heat transfer on blade coolant requirement, Appl. Thermal Eng. 129 (2018) 1403–1413.

[74] L. Zeng, P. Chen, X. Li, J. Ren, H. Jiang, Influence of simplifications of blade in gas turbine on film cooling performance, Appl. Thermal Eng. 128 (2018) 877–886.

[75] W. He, Q. Deng, W. Zhou, T. Gao, Z. Feng, Film cooling and aerodynamic performances of a turbine nozzle guide vane with trenched cooling holes, Appl. Thermal Eng. 150 (2019) 150–163.

[76] M. Maheshwari, O. Singh, Thermodynamic study of different configurations of gassteam combined cycles employing intercooling and different means of cooling in topping cycle, Appl. Thermal Eng. (2019) 114249.

[77] A.M. Abdala, F.N. Elwekeel, D. Huang, Film cooling effectiveness and flow structures for novel upstream steps, Appl. Thermal Eng. 105 (2016) 397–410.

[78] R.S. Bunker, A review of shaped hole turbine film-cooling technology, J. Heat Transfer 127 (2005) 441–453.

[79] A. Dhungel, Y. Lu, W. Phillips, S.V. Ekkad, J. Heidmann, Film cooling from a row of holes supplemented with antivortex holes, J. Turbomach. 131 (2009) 021007.

[80] K. Kusterer, N. Tekin, D. Bohn, T. Sugimoto, R. Tanaka, M. Kazari, "Experimental and numerical investigations of the NEKOMIMI film cooling technology," in ASME Turbo Expo, Turbine Tech. Conf. Exposition 2012 (2012) 1299–1310.

[82] J.S. Liu, M.F. Malak, L.A. Tapia, D.C. Crites, D. Ramachandran, B. Srinivasan, et al., "Enhanced film cooling effectiveness with new shaped holes," in ASME Turbo Expo, Power Land Sea Air 2010 (2010) 1517–1527.

[83] D.L. Rigby, J.D. Heidmann, "Improved film cooling effectiveness by placing a vortex generator downstream of each hole," in ASME Turbo Expo, Power Land Sea Air 2008 (2008) 1161–1174.

[84] R.S. Bunker, "Film cooling: breaking the limits of diffusion shaped holes," in ICHMT DIGITAL, LIBRARY ONLINE (2009).

[85] L. Hylton, M. Mihelc, E. Turner, D. Nealy, and R. York, "Analytical and experimental evaluation of the heat transfer distribution over the surfaces of turbine vanes," 1983.

[86] D. Bohn, Combined aerodynamic and thermal analysis of a high-pressure turbine nozzle guide vane, Proc. Yokohama IGTC 1 (1995) 35–39.

[87] J.D. Heidmann, A.J. Kassab, E.A. Divo, F. Rodriguez, E. Steinthorsson, "Conjugate heat transfer effects on a realistic film-cooled turbine vane," in ASME Turbo Expo 2003, collocated with the, Int. Joint Power Gener. Conf. 2003 (2003) 361–371.

[88] Z.-X. Han, B.H. Dennis, G.S. Dulikravich, Simultaneous prediction of external flowfield and temperature in internally cooled 3-D turbine blade material, Int. J. Turbo Jet Engines 18 (2001) 47–58.

[89] B. Facchini, A. Magi, A. Scotti Del Greco, "Conjugate heat transfer simulation of a radially cooled gas turbine vane," in ASME Turbo Expo, Power Land Sea Air 2004 (2004) 951–961.

[90] V. Esfahanian, A. Shahbazi, G. Ahmadi, "Conjugate Heat Transfer Simulation of Internally Cooled Gas Turbine Vane," in, Proceedings of the CFD Society of Canada Conference, (2012).

[91] J.E. Dees, D.G. Bogard, G.A. Ledezma, G.M. Laskowski, A.K. Tolpadi, Experimental measurements and computational predictions for an internally cooled simulated turbine vane, J. Turbomach. 134 (2012) 061003.

[92] J. Luo, E.H. Razinsky, Conjugate heat transfer analysis of a cooled turbine vane using the V2F turbulence model, J. Turbomach. 129 (2007) 773–781.

[93] W.D. York, D.K. Walters, J.H. Leylek, "A novel transition-sensitive conjugate methodology applied to turbine vane heat transfer," in ASME, Int. Mech. Eng. Congr. Expos. 2003 (2003) 55–65.

[94] K. Kusterer, D. Bohn, T. Sugimoto, R. Tanaka, "Conjugate calculations for a filmcooled blade under different operating conditions,", ASME Turbo Expo Power Land Sea Air 2004 (2004) 675–684.

[95] B. Wang, W. Zhang, G. Xie, Y. Xu, M. Xiao, Multiconfiguration shape optimization of internal cooling systems of a turbine guide vane based on thermomechanical and conjugate heat transfer analysis, J. Heat Transfer 137 (2015) 061004.

[96] D. L. Rigby and J. Lepicovsky, "Conjugate heat transfer analysis of internally cooled configurations," in ASME Turbo Expo 2001: Power for Land, Sea, and Air, 2001.

[97] T. Chmielniak, G. Nowak, "Coupled analysis of cooled gas turbine blades," in ASME Turbo Expo 2003, collocated with the, Int. Joint Power Generation Conf. 2003 (2003) 551–558.

[98] A.F. Chen, H.-W. Wu, N. Wang, J.-C. Han, Heat transfer in a rotating cooling channel (AR= 2: 1) with rib turbulators and a tip turning vane, J. Heat Transfer 140 (2018) 102007.

[99] T. Takahashi, K. Watanabe, T. Sakai, "Conjugate heat transfer analysis of a rotor blade with rib-roughened internal cooling passages,", ASME Turbo Expo Power Land Sea Air 2005 (2005) 275–284.

[100] K. Watanabe, T. Takahashi, "LES simulation and experimental measurement of fully developed ribbed channel flow and heat transfer,", ASME Turbo Expo Power Land Sea Air 2002 (2002) 411–417.