Published by Avanti Publishers
Journal of Advanced Thermal Science Research
ISSN (online): 2409-5826

A Short Introduction of Blade Cooling Mechanisms in Old Gas Turbines with the Aim of Proper Distribution of Temperature Profile

Kazem Reza Kashyzadeh[1,*] and Kambiz Souri[2]

[1]*Department of Transport,* [2]*Department of Energy Engineering, Academy of Engineering, RUDN University, 6 Miklukho-Maklaya St., Moscow 117198, Russian Federation*

ARTICLE INFO

Article Type: Research Article
Academic Editor: Ashok Kumar Singh
Keywords:
Blade
Gas turbine
Service life
Cooling mechanism
Temperature distribution
Timeline:
Received: November 18, 2023
Accepted: December 20, 2023
Published: December 29, 2023
Citation: Reza Kashyzadeh K, Souri K. A short introduction of blade cooling mechanisms in old gas turbines with the aim of proper distribution of temperature profile. J Adv Therm Sci Res. 2023; 10: 98-111.
DOI: https://doi.org/10.15377/2409-5826.2023.10.8

ABSTRACT

Presently, old gas turbines are used in the industry of some developing countries without high tech, which face many problems in the field of thermal efficiency and output power. Typically, turbines operate in the temperature range of 1200 to 1500 degrees Celsius. Many studies have been done to increase the efficiency of such systems. The results show that this increase in temperature at the inlet of the gas turbine has negative consequences, such as increasing the thermal load of the turbine blades and thus reducing the lifetime of the blades. On the other hand, a damaged blade can cause serious damage to other blades as well as the main shaft and other parts in various ways and sometimes lead to complete failure of the turbine. Therefore, it is reasonable to consider cost reduction considerations, including maintenance. Hence, due to the limitation of thermal stresses for the continuous operation of gas turbine blades, the distribution of heat transferred to them must be controlled. In this regard, the presence of blade cooling mechanisms is necessary for its safe operation, because the operating temperature of the gas turbine is much higher than the allowable temperature of the blades. In addition to cooling the blades, cooling the shell and inlet nozzle of gas turbines is also extremely important. But since the blades are exposed to high-level stress and tension for a long time, their cooling is more important and sensitive. For this reason, in the present article, the authors tried to provide a short introduction to the efficient mechanisms in cooling the blades related to the old systems, whose effect is noticeable on increasing the lifetime of the blades.

*Corresponding Author
Email: reza-kashi-zade-ka@rudn.ru
Tel: +(98) 912 076 8670

1. Introduction

The failure of turbine blades in various industries is known as one of the main challenges of mechanical, manufacturing, metallurgical, and materials engineers [1]. Despite the extensive research and the exorbitant costs of experts in this field, strange failures are recorded in this super-critical part daily, which sometimes cause irreparable damage to the industry. In general, some researchers in the industrial field believe that 50 to 90% of component failure during work is due to the destructive phenomenon of fatigue, because this phenomenon is not fully understood and subsequently it cannot be fully considered and controlled in the design phase [2, 3]. However, in recent years, very good criteria and methods have been proposed to predict the fatigue life of components under complex loading conditions, such as multi-inputs random amplitude [4, 5], but the predicted results are far from reality. Even in some industrial parts with complicated geometry (e.g., automotive steering knuckle), this difference can reach 100% error [6, 7]. Currently, this part (i.e., turbine blades) is not exempt from this issue and is constantly subjected to thermal cyclic loads and also works at very high temperatures, which leads to various damages such as creep [8-11], and creep-fatigue [12-16], etc. Industrialists believe that one of the most efficient solutions is the use of special materials, i.e., thermal barrier coatings [17], which are more resistant to corrosion and other destructive phenomena than metals. Accordingly, the blades are usually made of different types of Inconel, such as 738LC [18-20], 713LC [21, 22], 625 [23], and 617 [24]. In addition, to reduce defects and structural errors in the manufacturing process and prevent microstructural effects, recently turbine blades are made of single crystal so that crystal orientations cannot affect their mechanical properties [25-27]. Nevertheless, it is necessary to reduce the temperature gradient created in the blade by using different methods, and the best solution proposed by scholars is the use of a cooling mechanism. The coolants used in such systems are classified into two categories: air or liquid like water. At first glance, it seems that the liquid cooling system is more attractive than the air cooling system due to its high heat capacity and, as a result, better cooling. However, using liquid cooling system can cause many problems, including leakage and corrosion. On the other hand, the air cooling system allows the discharged air to enter the main stream without any problems. In this regard, by using air as much as 1-3% of the main flow, the temperature of the blades can be reduced in the range of 200 to 300 degrees Celsius compared to the initial state [28]. In summarizing the advantages and disadvantages of different cooling systems, the main focus of recent studies is solely on air cooling system. Many cooling methods that are used in gas turbine blades are impingement cooling, film cooling, effusion cooling, layer cooling, and pin fin cooling, etc. [29], which are classified into the categories of internal and external mechanisms. In the current research, internal cooling mechanism by holes and creating air passage inside the blade was discussed. In this case, there is no need for additional equipment and control of its compatibility with the entire system. Only during the production stage of the blade or after production, it is necessary to create holes according to its specific characteristics.

2. Reducing the Temperature Gradient Based on the Desired Cooling Mechanism

Han's 2004 research showed that if the coolant is passed through multiple rib-enhanced serpentine passages to remove incoming heat from the outer surface, the blades are cooled internally [30]. Additionally, if cooler air is injected outside the blade surface from external cooling passages, external cooling of the turbine blades can be achieved by film cooling to create a protective layer between the blade surface and hot gas-path flow. According to his belief, most experimental research is focused on the main body of the blade. However, a major concern in turbines is the cooling of the blade edge region, such as end-wall heat transfer and film cooling, blade trailing edge heat transfer by internal coolant injection along the trailing edge base, as well as blade tip region heat transfer with or without film cooling under engine flow conditions. To summarize, the local heat transfer data in the edge regions can play an effective role in engineering design. Therefore, in one of his studies, he published a brief summary of the results obtained in the turbine heat transfer laboratory of Texas A&M University from 1980 to 2004 [31]. Moreover, he mentioned that the influence of rotation on the heat transfer of rotor blade coolant is strongly emphasized in internal cooling with rib turbulators, pin fins, dimples, and impinging jets. Furthermore, external cooling focuses on the effects of high volatile free-stream turbulence on film cooling performance, which specifically emphasizes the problems of heat transfer and cooling of turbine blade edge region.

Takeishi *et al.* applied measurement by a heat-mass transfer analog and conducted a low-speed stationary cascade experiment to investigate the influence of film cooling on the rotation blade [32]. According to their findings, the film cooling effect on the suction surface of the rotating blade exactly matches that of the stationary blade. However, there is a low level of effectiveness on the pressure surface of the rotating blade. Glezer *et al.* proposed a new technique for internal blade cooling [33]. They conducted a study and their extensive research into convective (including impingement) and film cooling techniques led to significant improvements so as to gain high levels of cooling efficiency for turbine airfoils. However, in the case of turbine blades, there are severe limitations to the use of these techniques. High-performance Impingement cooling should be integrated with the spent air film discharge to negate the negative effect of cross-flow on internal heat transfer and to secure additional thermal protection of the surface downstream of the discharge holes. The application of blade film cooling can be restricted through remarkable aerodynamic penalties, stress concentration, and a significant increase in manufacturing cost, specifically for slightly elevated operating temperatures. In conclusion, the results demonstrate that compared to impingement coupled with film discharge of the spent air, which has higher efficiency than cross-flow impingement and is approximately five times higher than the heat transfer in a smooth channel, the leading edge screw-shaped cooling technique provides an internal heat transfer rate. A review report on computational fluid dynamics applied to gas turbine internal blade cooling has been published by Iacovides and Launder [34]. Modeling considerations were taken into consideration in their studies, and it was mentioned that their application is necessary for such a study. Adopting a low Reynolds number model for the sublayer region is a basic necessity. It has been proven that Rayleigh number effects can change heat transfer coefficients in the cooling passages by at least 50%. Furthermore, it has been proven that the use of second-moment closure in modeling can lead to a significant improvement in the quality of predictions.

Han and Rallabandi utilized the Pressure Sensitive Paint (PSP) technique to investigate the film cooling of turbine blades [35]. They investigated the effects of various factors, including blowing ratio, momentum ratio, density ratio, hole shape, surface geometry, and free-stream turbulence, on flat plates, turbine blades, vanes, and end-walls. Two models of internal and external cooling along with the details of the blade and its accessories are schematically shown in Fig. (**1**). In addition, the angles of the holes are designed to increase the effectiveness of cooling, e.g., Fig. (**2**) illustrates the definition of a compound angle. Finally, they concluded that the influence of rotation and unsteady speed, temperature profiles, and stator wake on rotor blade film cooling effectiveness and heat transfer coefficients is an under-investigated issue. Additionally, the effects of thermal barrier coating spallation, film cooling hole blockage, and surface roughness on the blade surface, end-walls, and tip are also worth studying.

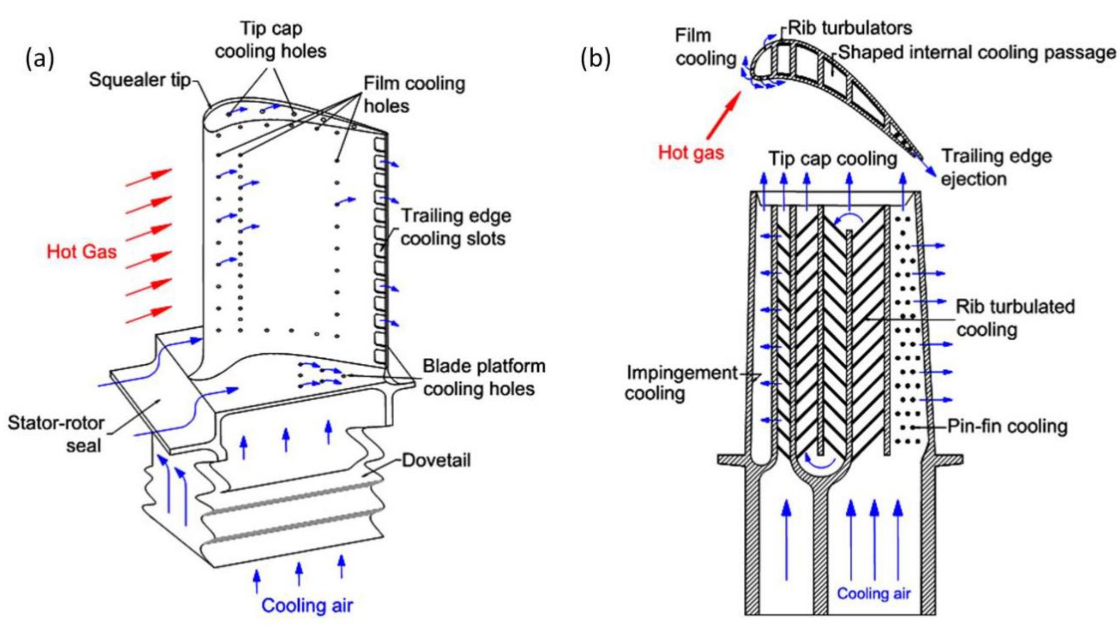


Figure 1: Schematic view of turbine blade cooling systems, including a) external cooling and b) internal cooling [35].

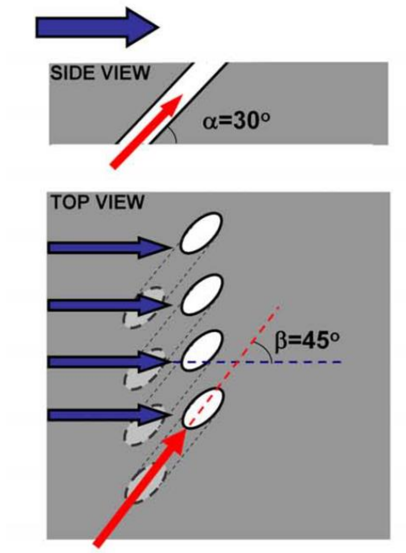


Figure 2: Definition of compound angle [35].

In addition to the study mentioned above, the compound angle variable has also been studied by Gao and Han [36]. In this regard, they considered two film cooling schemes:

1- Strongly film cooled leading edge featured with seven rows of film cooling holes.

2- Medium film cooled leading edge with three rows.

To design the seven-row scheme, film holes are placed at 0° (stagnation line), 15°, 30°, and 45° angles on the model surface. Meanwhile, for the design of three-row scheme, film holes are located at angles of 0° and 30°. Additionally, each scheme uses four different film cooling hole configurations, such as radial-angled cylindrical holes, compound-angled cylindrical holes, radial-angled shaped holes, and compound-angled shaped holes. The test was conducted in a wind tunnel at low speed. In addition, according to main stream velocity and cylinder diameter, the Reynolds number was 100 and 900. The main stream turbulence intensity was approximately 7% close to the leading edge model and the turbulence integral length scale was approximately 150 mm. Five medium blowing ratios, from M 0.5 to M 2.0, were tested. The results obtained in the current research are shown in Fig. (**3**). Accordingly, compared to cylindrical holes, shaped holes provide higher film cooling efficiency, specifically at higher blowing ratios. Compared to compound angle holes, the radial angle holes have a favorable performance at M 1.0-2.0. Also, compared to the three-row scheme, the film cooling design has a much higher efficiency in the leading edge region at the same average blowing ratio or same amount of coolant flow. Finally, as the average blowing ratio increases near the stagnation region, the film cooling efficiency increases in both schemes. However, in the downstream region, due to the mixing interaction between the cooling jets and the main steam flow, the efficiency decreases at higher blowing ratios.

Sanjay *et al.* conducted a comparative study on the effect of providing different means of turbine blade cooling on the thermodynamic performance of a CCPP [37]. In this research, seven cases including air and steam were considered as cooling under open- and closed- loop cooling techniques. In this regard, the open-loop uses internal convection, film, and transpiration cooling techniques. Additionally, the closed-loop cooling only includes internal convection cooling. Based on the obtained results, the closed-loop steam cooling shows a more specific operation and, as a result, yields a greater value of plant efficiency of approximately 60%. In contrast, it has been proven that open-loop transpiration steam cooling, open-loop steam internal convection cooling, transpiration air cooling, film steam cooling, film air, and internal convection air cooling provide lower values of plant effectiveness in reducing order than closed-loop steam cooling. The findings of the current research are summarized as follows:

(i) Considering all cooling devices, the minimum and maximum cooling flow requirements are provided by closed-loop steam cooling and air internal convection cooling, respectively.

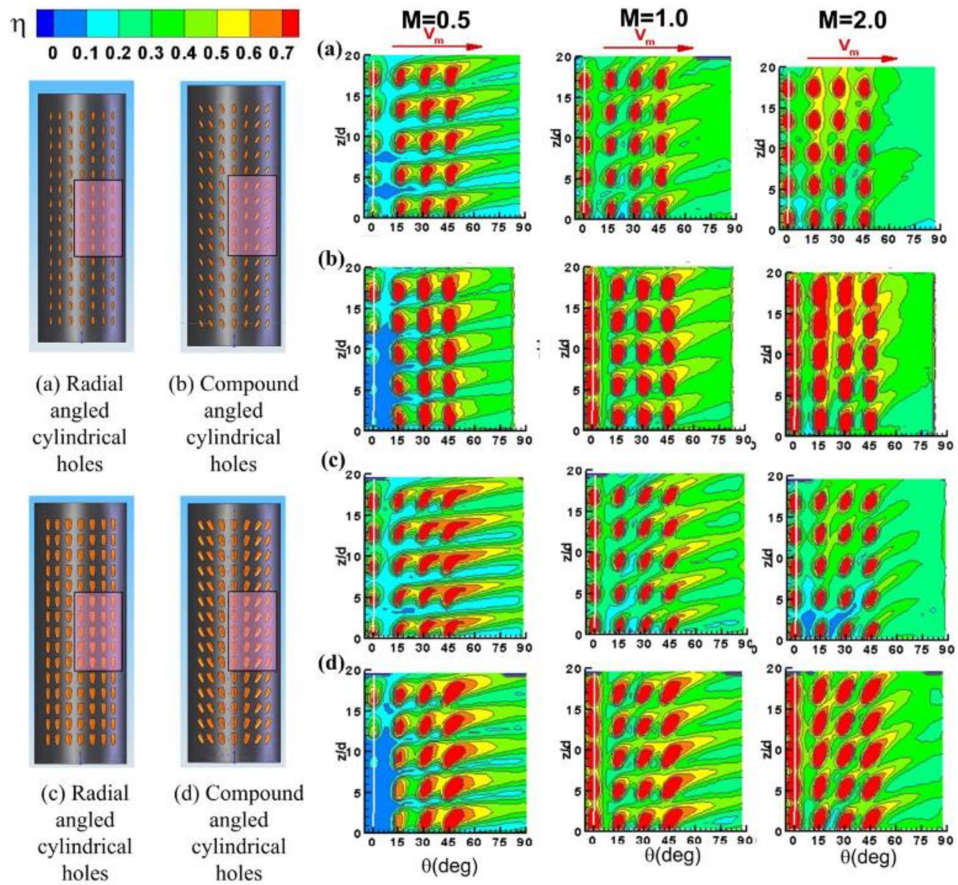


Figure 3: Effects of film-hole shape and angle presented by Gao and Han [36].

(ii) The optimum turbine inlet temperature which can be presented for a differential pressure ratio of a combined cycle compressor with air cooling means is fixed at 1600 K. However, regarding steam cooling, no optimum value of turbine inlet temperature is available and higher values give better performance.

(iii) Whatever the turbine inlet temperature, the work done in the plant decreases linearly with increasing compressor pressure ratio for all cooling devices. However, due to different reactions of the compressor pressure ratio and the turbine inlet temperature, there must be an agreement on the optimum compressor pressure ratio.

(iv) There is an increase in plant efficiency and operation with a permissible blade temperature for a constant value of the turbine inlet temperature for all cooling devices.

(v) The plant efficiency of closed-loop steam cooling is maximized by using all the cooling systems. In contrast, transpiration air cooling is better than other air cooling means.

(vi) Of all the cooling means, the closed-loop steam cooling has the highest efficiency for the plant and given work. According to the effectiveness of the plant and given work of other cooling means, in decreasing order of performance is open-loop transpiration steam cooling, transpiration air cooling, film steam cooling, film air cooling, and internal convection air cooling.

Findings from searches conducted between 2001 and 2010 on blade tip leakage flow related to heat transfer, and external or internal tip cooling technologies were analyzed by Sunden and Xie [38]. The complex phenomena of flow and heat transfer in the gas turbine path are illustrated in Fig. (**4**). The results of this study indicate that the blade tip is the most sensitive area under high thermal load, and it is challenging to cool it completely. A common technique for external cooling is to add coolant through the tip and near-tip area. Parameters such as film cooling hole configuration, location, distribution, and representative flow conditions mainly affect cooling performance. It is possible to design serpentine cooling passages inside the blades for internal cooling so that coolant extracted from the compressor can absorb heat from the pressure side and the suction side. The effectiveness of internal cooling can be significantly affected by serpentine channel configuration, aspect ratio, orientation, rib configuration and location, and rotation and bend/turn geometry.

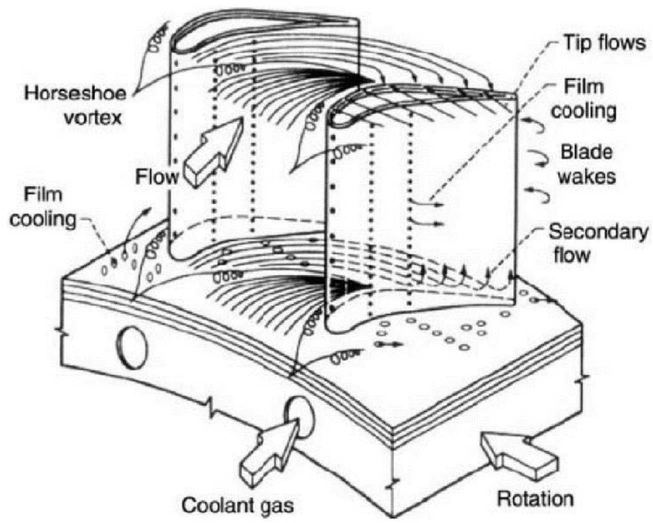
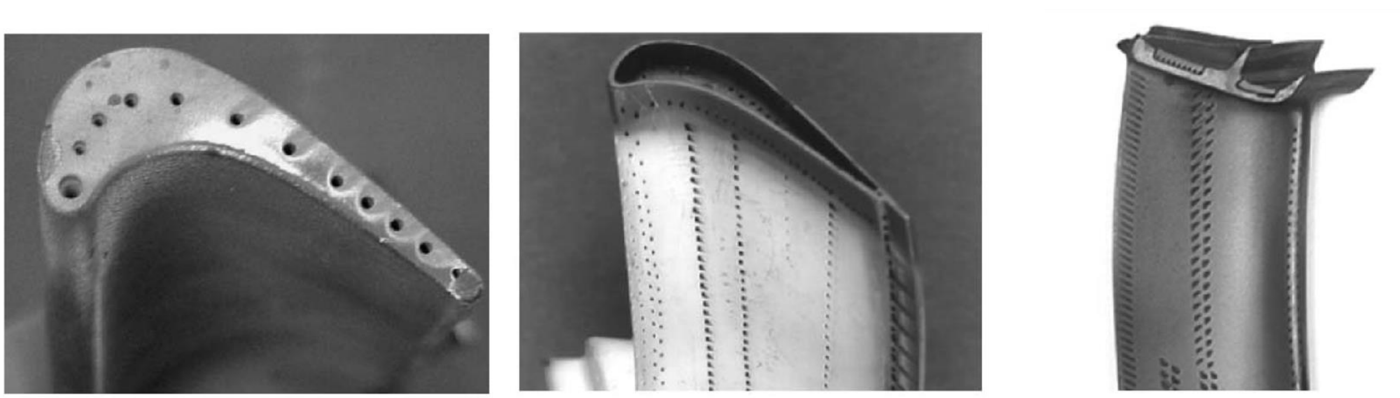


Figure 4: The complex phenomena of flow and heat transfer in the gas turbine path [38].

Bunker focused on design and durability issues of axial turbine blade tips [39]. Next, the different types of blade tips considered in this study are shown in Fig. (**5**). Many studies have been conducted in the field of turbine blade cooling systems and its effects on system efficiency, including the distribution of temperature characteristics in the blade [40-45].



a) Blade flat/plane tip **b) Blade squealer tip** **c) Blade with attached tip shroud**

Figure 5: Different types of blade tips, including **a**) blade flat/plane tip, **b**) blade squealer tip, and **c**) blade with attached tip shroud [39].

Nowak and Wróblewski optimized the blade cooling system by an evolutionary algorithm within a 3D design space that uses the Pareto approach [46]. Furthermore, they reported that the obtained results were more reliable thermal field predictions compared to the classical approach. For this purpose, the problem was solved for a well-known reference profile, C3X, which was extensively investigated by NASA [47]. In this regard, the vane profile is assumed to be aerodynamically optimal and constant during the calculation process. The vane in question was originally a convectively cooled one with ten internal passages, as demonstrated in Fig. (**6**). In this research, the number of holes was considered equal to 10, and the parameters of the diameter of the holes and their location were considered as input variables in the optimization algorithm. In addition, multiple objective functions including reduction of the temperature distribution coefficient and temperature gradient in the blade were considered. Despite the original model, two optimal models were presented, the details of which are given along with the temperature distribution contour in Fig. (**7**).

Stagger angle, deg	59.89
Pitch, mm	117.7
Chord, mm	144.9
Axial chord, mm	78.2
High, mm	76.2

Hole	d mm	m_c g/s	T_{tc} K
1	6.3	16.7	348.3
2	6.3	17.4	349.7
3	6.3	14.8	340.0
4	6.3	16.5	341.5
5	6.3	17.5	331.4
6	6.3	16.5	361.4
7	6.3	16.1	338.2
8	3.1	5.5	363.1
9	3.1	3.49	383.2
10	1.98	1.71	390.9

p_{2c}=0.275MPa, Tu_c=10%

Figure 6: Details of the original C3X airfoil geometry [46].

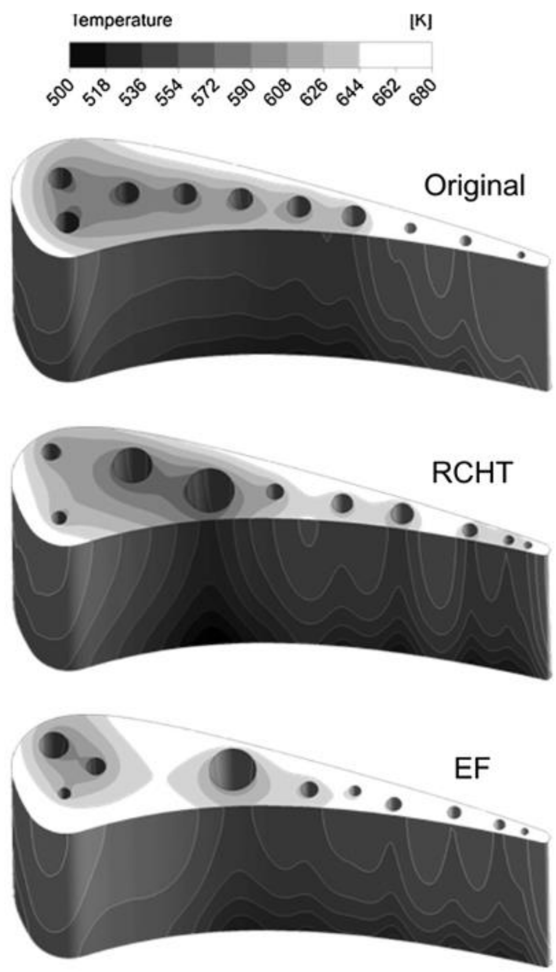


Figure 7: Temperature distribution on the blade surface for the reference case and optimized models [46].

Moreover, the wall temperature distribution for different models is depicted in Fig. (**8**). It is clear that the EF model is the most optimal if the surface temperature distribution is considered. However, based on the data in Fig. (**8**), it is obvious that the RCHT model is the optimal model with respect to the wall temperature distribution. Therefore, if the target is the simulation area of the blade surface and wall, a new model between RCHT and EF should be provided, or the targets should be prioritized. Then it should be determined which model is optimal and leads to an increase in the efficiency of the blade. Other similar works have been done on this particular case considering 10 cooling holes and optimizing in different ways [48]. The path taken by an equivalent study is almost identical, and they also presented consistent results.

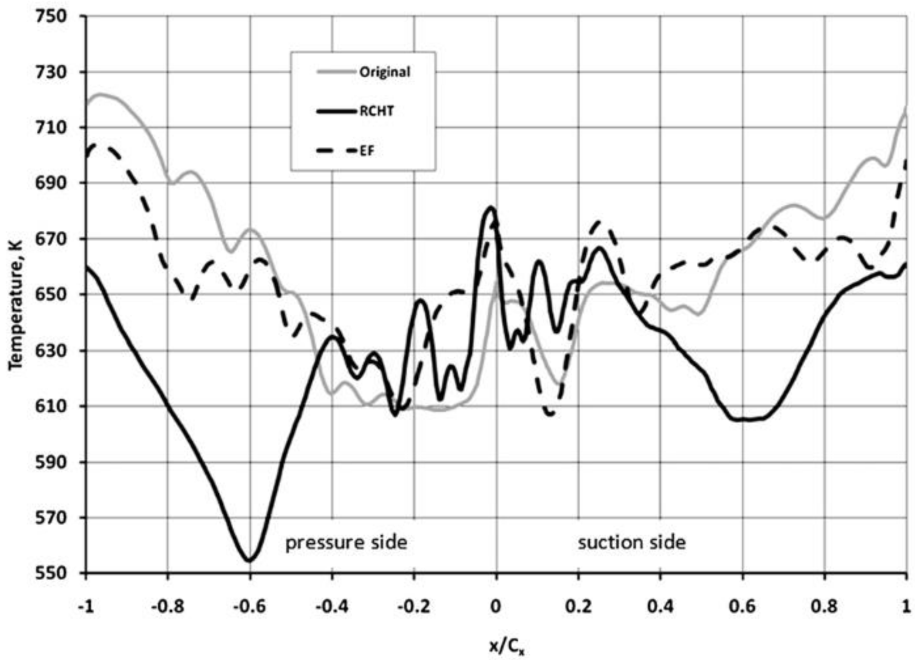


Figure 8: The wall temperature distribution on the profile for the reference case and optimized models [46].

Mazaheri *et al.* optimized cooling of turbine blades using the same idea [49]. The difference between the present work and the previous research is that they did not consider 10 holes, and only 4 paths were considered for cooling, and the most focus was on the geometric shape of these holes, which are not symmetrical. In other words, it can be said that the surface is divided into four parts and the holes of each part are connected to create a larger hole, which shows that the temperature distribution on the surface is improved, and the maximum temperature is decreased in comparison with the initial state. The evolution of these changes is shown in Fig. (**9**). And the temperature distribution in the blades has been extracted using simulation software (Fig. **10**). Moreover, the temperature gradient contours are shown in Fig. (**11**).

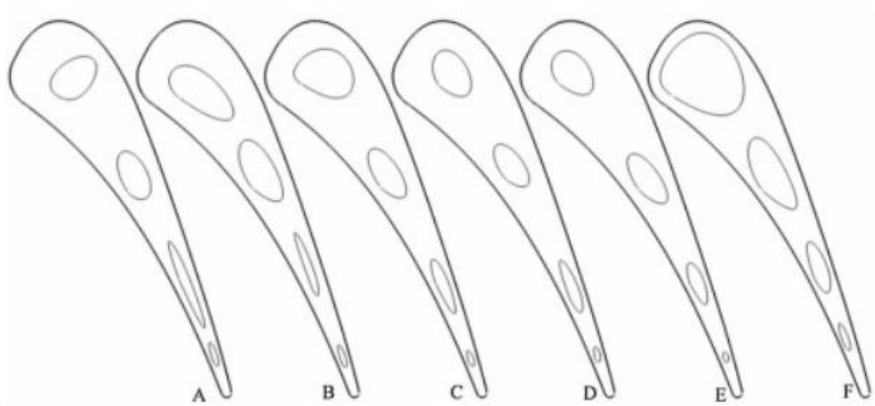


Figure 9: Shape and position of the internal passage in the cooling of turbine blades [49].

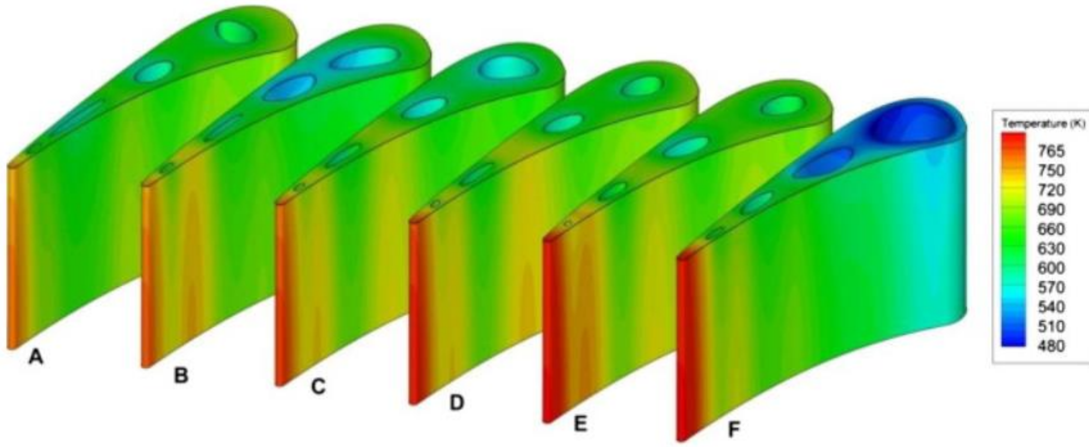


Figure 10: Temperature distribution for five optimal designs [49].

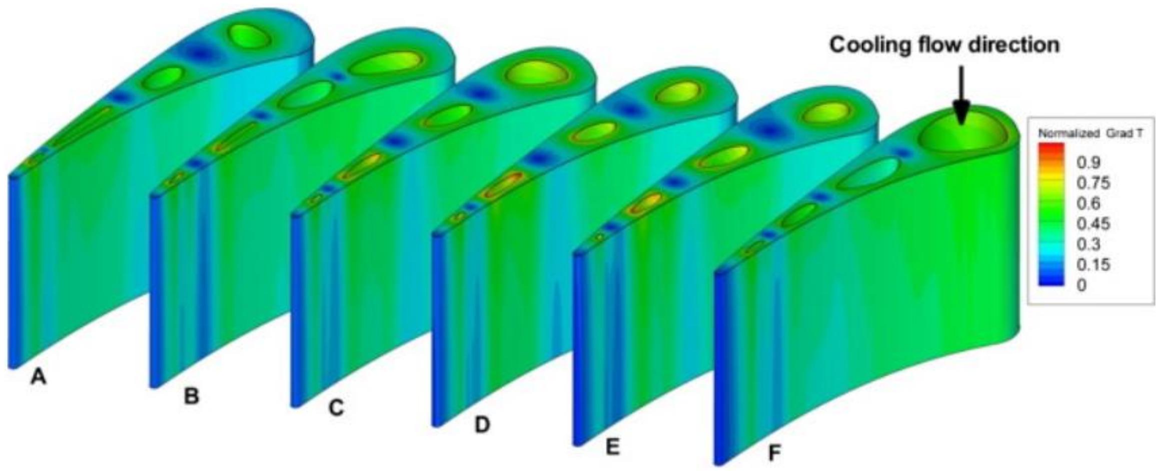


Figure 11: Normalized temperature gradient contours with maximum values for each optimal design [49].

Finally, it is concluded that with the last optimization step, both temperature distribution and temperature gradient parameters on the blade surface and wall are improved. However, the most important concern that the authors did not consider, which according to some researchers is important for other issues, is that the temperature of the blade tip is higher at the optimal state than other cases, or the maximum temperature is in the greater range of the surface. This causes the blade tip to be damaged more quickly and in effect reduces the service life of the blade. Therefore, one of the most important parameters that scholars have not paid much attention to is the main goal of optimization, which should be the service life of the blade. As a result, knowing the critical area prone to failure or damage in industrial parts is very important and can only be detected by simulating and performing coupled thermal-structural analysis for this part or examining the failures of real samples in a long-run history. In this regard, Amaral *et al.* performed a finite element simulation of the cooling process in the C3X airfoil by performing a thermal-structural coupling analysis [50]. In addition to the temperature distribution contours, they showed the thermal stress contours created in the component using the von Mises equivalent stress criterion and compared the component in two states without and with the cooling system.

According to the extensive research that has been done in the field of designing and optimizing cooling mechanisms of the blades, they still fail in the industry and sometimes cause great damage and in some cases, cause the entire system to fail. As mentioned earlier, the important issue is the effect of this temperature distribution on the service life of the blades. In summary, it is necessary to directly study the effect of cooling different areas of the blade, such as its tip, on increasing the fatigue life under thermal cyclic loading, creep, or fatigue-creep loading based on the working conditions of the blade. Therefore, this issue will be examined in a more specialized manner.

Research on the fatigue failure of blades is divided into several general categories:

1- Prediction of the fatigue life or service life of the blade by considering different working conditions;

2- Improving the fatigue life of the blade using different methods like laser shock peening;

3- Examining the effect of various functional or structural parameters on the fatigue life of the blade, such as cooling rate.

According to the aforementioned cases, numerous experimental, theoretical, and numerical studies have been carried out. However, each of the mentioned areas is susceptible to development on behalf of the progress of science and technology. For instance, the effect of crystal orientations on the fatigue life of single crystal cooled turbine blades was investigated by Hou *et al.* [51]. According to their report, due to the influence of temperature distribution and the complexity of the cooling tunnel, there is no proportionality between the location of maximum shear stress in the blade and the most dangerous location. Therefore, it is recommended to consider the stress and temperature field for the design of the cooled blade. Furthermore, the mechanical behavior of the single crystal and the fatigue life of the cooled blade can be affected by the axial and randomness orientation. The effect on the von Mises stress distributions and the maximum shear stress can be limited by the randomness of the two paths. However, the axial path deviation of the blade has a prominent effect on the stress distribution. Hence, the influence of deviation and randomness orientations on fatigue life is evident.

A fatigue life prediction model covering high-temperature applications of metallic materials has been proposed by Gallerneau and Chaboche [52]. The validity of this model is only related to multiaxial and non-proportional loading. The model recognizes the distinguish between the crack initiation and propagation, and also considers the effects of oxidation and creep on fatigue life. One of the applications of this model is for a coated single-crystal super alloy in turbine blades. Some predictions were made on the fatigue life of fan blades in the ventilation cooling system of the high-speed train by He *et al.* [53]. The current study developed a modified method according to the nominal stress method for predicting the fatigue life of centrifugal fan blades. Moreover, the application of the finite element model for the analysis of the state and stress of fan blades is typical based on the material properties. Afterward, the fatigue life assessment is based on the physical curve and using Miner's cumulative damage rule to calculate the total damage. According to the test results of small-scale specimens, a new method to evaluate the fatigue life of service-exposed industrial gas turbine blades was proposed by Holländer *et al.* [54]. Furthermore, optical microscopy was used to investigate fatigue crack paths. In the current study, the impact of service-induced microstructural changes on the tensile and cyclic properties of gas turbine blades made of conventionally cast nickel-base superalloy Inconel 738 has been investigated.

To increase the fatigue life of wind turbine rotor blades, Adam *et al.* used glass fiber composite reinforced by nanoparticles [55]. This study experimentally investigates the effects of boehmite nanoparticles on viscosity, static properties, and fatigue life. Based on rheological analysis, there is a remarkable increase in viscosity in the case of pristine boehmite particles. In contrast, the increase in viscosity can be remarkably reduced by modifying the surface the particles with excess taurine. Based on the tests, there was a remarkable increase in static properties as well as fatigue. If 15 wt.% of boehmite particles are added, it increases the fatigue life by up to 270% compared to unmodified fiber-reinforced epoxy. Finally, the results demonstrate that if the particle content increases, the fatigue limit increases.

To enhance Low-Cycle Fatigue (LCF) and High-Cycle Fatigue (HCF) of cast and forged turbine blades, Chen *et al.* benefited Laser Shock Peering (LSP) treatment [56]. In the current study, a full-scale fatigue test was conducted on the turbine blade. Furthermore, a probabilistic approach was used to investigate the effect of LSP treatment. Based on the results, LSP undoubtedly increased the fatigue life of both cast and forged blades, and the effect of LSP on cast blades was more obvious. Moreover, the threshold vibration stress was available for both cast and forged blades, and if the vibration stress was below the threshold vibration stress, there would be a tendency for the fatigue life to be prolonged by LSP. A supplementary study was also conducted to prove that due to the existence of compressive residual stress and refined grains caused by LSP, undoubtedly, there were fewer crack initiation sources in LSP blades, and the life of LSP blades was longer.

3. Conclusion

According to the data collected in the literature review, it is clear that the use of air cooling is much more suitable than a liquid, such as water, because it avoids destructive phenomena such as corrosion and erosion due to the proximity to water. Therefore, the main focus of this study was on air as a coolant. On the other hand, in order to optimize the geometry of the blade and reduce the temperature distribution and temperature gradient at the blade tip, a parametric analysis can be performed and different geometric variables, including angle and curvature, can be changed in different parts, such as convex parts. In this case, we will have a better temperature on the surface, wall, and tip of the blade, but if this design is changed, it can lead to a mistake in the aerodynamic performance. Therefore, complex and time-consuming calculations must be considered for blade aerodynamics and vibration and stability issues, etc. Research in recent years has also shown that most scientists are looking to use an internal cooling mechanism, which avoids adding separate equipment to the system and complicating the setup. In addition, the results show that the use of internal cooling, such as creating holes with suitable sizes, shapes, and even location, can have a significant effect on the temperature distribution and temperature gradient of the blade. But the point that was not observed in the reviewed articles was the evaluation of the fatigue life of the blade in terms of internal cooling rate.

4. Future Research Plans

According to the studies conducted by the researchers and their achievements, the following topics were presented as suggestions for future research that the authors will address in the near future.

- Prediction of blade fatigue life with and without internal cooling mechanism;
- Using different optimization methods in order to provide the optimal cooling mechanism by the holes, including some parameters (number, size, and optimal location) in order to increase fatigue life of the blade;
- Investigating the effect of the cooling rate of turbine blades on the fatigue life of the blades;
- Investigating creep-fatigue failure mechanisms in turbine blades;
- Providing new methodology for predicting the service life of turbine blades under the simultaneous effects of fatigue and creep phenomena at high temperature.

Nomenclature

PSP = Pressure Sensitive Paint

LCF = Low-Cycle Fatigue

HCF = High-Cycle Fatigue

LSP = Laser Shock Peening

CCPP = Combined Cycle Power Plant

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no financial support.

Acknowledgments

This paper has been supported by the RUDN University Strategic Academic Leadership Program.

Availability of Data and Material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Ridha WKM, Kashyzadeh RK, Ghorbani S. Common failures in hydraulic kaplan turbine blades and practical solutions. Materials. 2023; 16(9): 3303. https://doi.org/10.3390/ma16093303

[2] Kashyzadeh KR, Arghavan A. Study of the effect of different industrial coating with microscale thickness on the CK45 steel by experimental and finite element methods. Strength Mater. 2013; 45: 748-57. https://doi.org/10.1007/s11223-013-9510-x

[3] Arghavan A, Reza Kashyzadeh K, Asfarjani, AA. Investigating effect of industrial coatings on fatigue damage. Appl Mech Mater. 2011; 87: 230-37. https://doi.org/10.4028/www.scientific.net/AMM.87.230

[4] Kashyzadeh KR. A new algorithm for fatigue life assessment of automotive safety components based on the probabilistic approach: The case of the steering knuckle. Eng Sci Technol. 2020; 23(2): 392-404. https://doi.org/10.1016/j.jestch.2019.05.011

[5] Kashyzadeh KR, Farrahi GH, Shariyat M, Ahmadian MT. Experimental accuracy assessment of various high-cycle fatigue criteria for a critical component with a complicated geometry and multi-input random non-proportional 3D stress components. Eng Fail Anal. 2018; 90: 534-53. https://doi.org/10.1016/j.engfailanal.2018.03.033

[6] Shariyat M. New multiaxial HCF criteria based on instantaneous fatigue damage tracing in components with complicated geometries and random non-proportional loading conditions. Int J Damage Mech. 2010; 19(6): 659-90. https://doi.org/10.1177/1056789509338317

[7] Shariyat M. Three energy-based multiaxial HCF criteria for fatigue life determination in components under random non-proportional stress fields. Fatigue Fract Eng Mater Struct. 2009; 32(10): 785-808. https://doi.org/10.1111/j.1460-2695.2009.01381.x

[8] Marahleh G, Kheder ARI, Hamad HF. Creep-life prediction of service-exposed turbine blades. Mater Sci. 2006; 42: 476-81. https://doi.org/10.1007/s11003-006-0103-8

[9] Puspitasari P, Andoko A, Kurniawan P. Failure analysis of a gas turbine blade: A review. IOP Conf Ser Mater Sci Eng. 2011; 1034(1): 012156. https://doi.org/10.1088/1757-899X/1034/1/012156

[10] Karaivanov VG, Mazzotta DW, Chyu MK, Slaughter WS, Alvin MA. Three-dimensional modeling of creep damage in airfoils for advanced turbine systems. Proceedings of the ASME Turbo Expo 2008: Power for Land, Sea, and Air. Volume 5: Structures and Dynamics, Parts A and B. Berlin, Germany: June 9-13, 2008, pp. 225-234. https://doi.org/10.1115/GT2008-51278

[11] Liu D, Li H, Liu Y. Numerical simulation of creep damage and life prediction of superalloy turbine blade. Math Probl Eng. 2015; 2015: 732502. https://doi.org/10.1155/2015/732502

[12] Vacchieri E, Holdsworth SR, Costa A, Poggio E, Riva A, Villari P. Creep–fatigue interaction in two gas turbine Ni based superalloys subjected to service-like conditions. Mater High Temp. 2014; 31(4): 348-56. https://doi.org/10.1179/0960340914Z.00000000052

[13] Yan X, Nie J. Creep-fatigue tests on full scale directionally solidified turbine blades. J Eng Gas Turbines Power. 2008; 130(4): 044501. https://doi.org/10.1115/1.2901174

[14] Sun D, Ma G, Wan Z, Gao J. Study on creep-fatigue interaction mechanism and life prediction of aero-engine turbine blade. Eng Fail Anal. 2023; 154: 107715. https://doi.org/10.1016/j.engfailanal.2023.107715

[15] Paulose N, Fernando CD, Banerjee A, Sahu JK, Narendra Babu SN. Creep–fatigue interaction study on gas turbine engine alloy. In Chaari F, Gherardini F, Ivanov V, Haddar M, Eds., Lecture Notes in Mechanical Engineering. 2018; pp. 323-33. https://doi.org/10.1007/978-981-10-6002-1_25

[16] Poursaeidi E, Kavandi A, Torkashvand K. Study of creep–fatigue crack growth behavior in a gas turbine casing. J Fail Anal Preven. 2018; 18: 1607-15. https://doi.org/10.1007/s11668-018-0559-5

[17] Igumenov IK, Aksenov AN. Thermal barrier coatings on gas turbine blades: Chemical vapor deposition. Therm Eng. 2017; 64: 865-73. https://doi.org/10.1134/S0040601517120035

[18] Mazur Z, Luna-Ramirez A, Juárez-Islas JA, Campos-Amezcua A. Failure analysis of a gas turbine blade made of Inconel 738LC alloy. Eng Fail Anal. 2005; 12(3): 474-86. https://doi.org/10.1016/j.engfailanal.2004.10.002

[19] Bannazadeh R, Riahi M, Aieneravaie M. Failure analysis of a gas turbine blade made of inconel 738LC super alloy. Amirkabir J Mech Eng. 2018; 50(1): 103-12. https://doi.org/10.22060/mej.2016.773

[20] Vaezi M, Soleymani M. Creep Life prediction of inconel 738 gas turbine blade. J Appl Sci. 2009; 9(10): 1950-5. https://doi.org/10.3923/jas.2009.1950.1955

[21] Bonakdar A, Molavi-Zarandi M, Chamanfar A, Jahazi M, Firoozrai A, Morin E. Finite element modeling of the electron beam welding of Inconel-713LC gas turbine blades. J Manuf Process. 2017; 26: 339-54. https://doi.org/10.1016/j.jmapro.2017.02.011

[22] Chamanfar A, Jahazi M, Bonakdar A, Morin E, Firoozrai A. Cracking in fusion zone and heat affected zone of electron beam welded Inconel-713LC gas turbine blades. Mater Sci Eng A. 2015; 642: 230-40. https://doi.org/10.1016/j.msea.2015.06.087

[23] Patsa CK, Mohammed S. Structural analysis of super alloy gas turbine blade using fea. Int J Eng Res Technol. 2014; 3(1): 3068-72.

[24] Khan MA, Sundarrajan S, Natarajan S. Influence of plasma coatings on Inconel 617 for gas turbine applications. Surf Eng. 2014; 30(9): 656-61. https://doi.org/10.1179/1743294414Y.0000000296

[25] Ma D. Novel casting processes for single-crystal turbine blades of superalloys. Front Mech Eng. 2018; 13(1): 3-16. https://doi.org/10.1007/s11465-018-0475-0

[26] Arakere NK, Swanson G. Effect of crystal orientation on fatigue failure of single crystal nickel base turbine blade superalloys. J Eng Gas Turbines Power. 2002; 124(1): 161-76. https://doi.org/10.1115/1.1413767

[27] Angel NM, Basak A. On the fabrication of metallic single crystal turbine blades with a commentary on repair via additive manufacturing. J Manuf Mater Process. 2020; 4(4): 101. https://doi.org/10.3390/jmmp4040101

[28] Sinha A, Swain B, Behera A, Mallick P, Samal SK, Vishwanatha HM, Behera A. A review on the processing of aero-turbine blade using 3D print techniques. J Manuf Mater Process. 2022; 6(1): 16. https://doi.org/10.3390/jmmp6010016

[29] Xu L, Sun Z, Ruan Q, Xi L, Gao J, Li Y. Development trend of cooling technology for turbine blades at super-high temperature of above 2000 K. Energies. 2023; 16(2): 668. https://doi.org/10.3390/en16020668

[30] Han JC. Recent studies in turbine blade cooling. Int J Rotat Mach. 2004; 10(6): 443-57. https://doi.org/10.1155/S1023621X04000442

[31] Han JC. Turbine blade cooling studies at Texas A&M University: 1980-2004. J Thermophys Heat Transf. 2006; 20(2): 161-87. https://doi.org/10.2514/1.15403

[32] Takeishi K, Aoki S, Sato T, Tsukagoshi K. Film cooling on a gas turbine rotor blade. J Turbomach. 1992; 114(4): 828-34. https://doi.org/10.1115/1.2928036.

[33] Glezer B, Moon HK, O'Connell T. A novel technique for the internal blade cooling. In Turbo Expo: Power for Land, Sea, and Air. American Society of Mechanical Engineers;1996; 78750: V004T09A015. https://doi.org/10.1115/96-GT-181

[34] Iacovides H, Launder BE. Computational fluid dynamics applied to internal gas-turbine blade cooling: a review. Int J Heat Fluid Flow. 1995; 16(6): 454-70. https://doi.org/10.1016/0142-727X(95)00072-X

[35] Han JC, Rallabandi A. Turbine blade film cooling using PSP technique. Front Heat Mass Transf. 2010; 1(1): 013001. http://dx.doi.org/10.5098/hmt.v1.1.3001

[36] Gao Z, Han JC. Influence of film-hole shape and angle on showerhead film cooling using PSP technique. J Heat Transf. 2009; 131(6): 061701. https://doi.org/10.1115/1.3082413

[37] Singh SO, Prasad BN. Influence of different means of turbine blade cooling on the thermodynamic performance of combined cycle. Appl Therm Eng. 2008; 28(17-18): 2315-26. https://doi.org/10.1016/j.applthermaleng.2008.01.022

[38] Sunden B, Xie G. Gas turbine blade tip heat transfer and cooling: a literature survey. Heat Transf Eng. 2010; 31(7): 527-54. https://doi.org/10.1080/01457630903425320

[39] Bunker RS. Axial turbine blade tips: function, design, and durability. J Propul Power. 2006; 22(2): 271-85. https://doi.org/10.2514/1.11818

[40] Ito S, Goldstein RJ, Eckert ER. Film cooling of a gas turbine blade. J Eng Gas Turbines Power. 1978; 100(3): 476-81. https://doi.org/10.1115/1.3446382

[41] Dring RP, Blair MF, Joslyn HD. An experimental investigation of film cooling on a turbine rotor blade. J Eng Gas Turbines Power. 1980; 102(1): 81-7. https://doi.org/10.1115/1.3230238

[42] Joo J, Durbin P. Simulation of turbine blade trailing edge cooling. J Fluids Eng. 2009; 131(2): 021102. https://doi.org/10.1115/1.3054287

[43] Han JC, Huh M. Recent studies in turbine blade internal cooling. In TURBINE-09. Proceedings of International Symposium on Heat Transfer in Gas Turbine Systems. Antalya, Turkey: August 9-14, 2009. https://doi.org/10.1615/ICHMT.2009.HeatTransfGasTurbSyst.460

[44] Han JC, Ekkad S. Recent development in turbine blade film cooling. Int J Rotating Mach. 2001; 7(1): 21-40. https://doi.org/10.1155/S1023621X01000033

[45] Wilcock RC, Young JB, Horlock JH. The effect of turbine blade cooling on the cycle efficiency of gas turbine power cycles. J Eng Gas Turbines Power. 2005; 127(1): 109-20. https://doi.org/10.1115/1.1805549

[46] Nowak G, Wróblewski W. Optimization of blade cooling system with use of conjugate heat transfer approach. Int J Thermal Sci. 2011; 50(9): 1770-81. https://doi.org/10.1016/j.ijthermalsci.2011.04.001

[47] Hylton LD, Mihelc MS, Turner ER, Nealy DA, York RE. Analytical and experimental evaluation of the heat transfer distribution over the surfaces of turbine vanes. 1983; Document ID: 19830020105. Available from: https://ntrs.nasa.gov/api/citations/19830020105/downloads/19830020105.pdf

[48] Storti B, Garelli L, Storti M, D'elia J. Optimization of an internal blade cooling passage configuration using a Chimera approach and parallel computing. Finite Elem Anal Des. 2020; 177: 103423. https://doi.org/10.1016/j.finel.2020.103423

[49] Mazaheri K, Zeinalpour M, Bokaei HR. Turbine blade cooling passages optimization using reduced conjugate heat transfer methodology. Appl Therm Eng. 2016; 103: 1228-36. https://doi.org/10.1016/j.applthermaleng.2016.05.007

[50] Amaral S, Verstraete T, Van den Braembussche R, Arts T. Design and optimization of the internal cooling channels of a high pressure turbine blade—part I: methodology. J Turbomach. 2010; 132(2): 021013. https://doi.org/10.1115/1.3104614

[51] Hou NX, Gou WX, Wen ZX, Yue ZF. The influence of crystal orientations on fatigue life of single crystal cooled turbine blade. Mater Sci Eng: A. 2008; 492(1-2): 413-8. https://doi.org/10.1016/j.msea.2008.03.043

[52] Gallerneau F, Chaboche JL. Fatigue life prediction of single crystals for turbine blade applications. Int J Damage Mech. 1999; 8(4): 404-27. https://doi.org/10.1177%2F105678959900800407

[53] He N, Feng P, Li ZW, Tan LG, Pang T, Chen YZ, Yang C. Fatigue life prediction of centrifugal fan blades in the ventilation cooling system of the high-speed-train. Eng Fail Anal. 2021; 124: 105373. https://doi.org/10.1016/j.engfailanal.2021.105373

[54] Holländer D, Kulawinski D, Weidner A, Thiele M, Biermann H, Gampe U. Small-scale specimen testing for fatigue life assessment of service-exposed industrial gas turbine blades. Int J Fatigue. 2016; 92: 262-71. https://doi.org/10.1016/j.ijfatigue.2016.07.014

[55] Adam TJ, Exner W, Wierach P. Taurine-Modified Boehmite Nanoparticles for GFRP Wind Turbine Rotor Blade Fatigue Life Enhancement. Materials. 2021; 14(22): 6997. https://doi.org/10.3390/ma14226997

[56] Chen C, Zhang XY, Yan XJ, Ren J, Huang DW, Qi MJ. Effect of laser shock peening on combined low-and high-cycle fatigue life of casting and forging turbine blades. J Iron Steel Res Int. 2018; 25(1): 108-19. https://doi.org/10.1007/s42243-017-0013-z