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COOLING SYSTEM ANALYSIS OF GAS TURBINE BLADES MANUFACTURED USING DIFFERENT MATERIAL TYPES

İbrahim Can[1], *Serdar Mercan*[2], *Doğan Engin Alnak*[1] *Muhammed Sipahi*[*1]

[1]*Department of Manufacturing Engineering, Faculty of Technology, Sivas Cumhuriyet University, Sivas, Turkey*
[2]*Department of Mechatronics Engineering, Faculty of Technology, Sivas Cumhuriyet University, Sivas, Turkey*

Abstract

Original scientific paper

One of the major challenges in gas turbine engines is that the blades operate at temperatures higher than the melting points of the materials they are made of. Researchers have focused on developing materials that can withstand high temperatures and designing effective cooling systems for the blades. Although there are limitations to the improvements that can be achieved through material technology, the importance of cooling is clear, and it is considered a critical factor for achieving high efficiency in turbines. To this end, two cooling models were developed using different materials, and the heat transfer in the blades was analyzed numerically using the SolidWorks package program and Ansys. The study considered titanium carbide (TiC) and third-generation single crystal super-alloy CMSX-10 materials. The blade designs were proposed based on the analysis results. The analysis showed that the enhanced model performed better when used with CMSX-10 material in terms of thermal properties.

Keywords: *Turbine blade, blade cooling, TiC, CMSX-10.*

FARKLI MALZEME TÜRLERİ KULLANILARAK ÜRETİLEN GAZ TÜRBİNİ KANATLARININ SOĞUTMA SİSTEMİ ANALİZİ

Özet

Orijinal bilimsel makale

Gaz türbini motorlarındaki en büyük zorluklardan biri, türbin kanatlarının yapıldıkları malzemelerin erime noktalarından daha yüksek sıcaklıklarda çalışmasıdır. Bu sorunu çözmek amacıyla, araştırmacılar yüksek sıcaklıklara dayanabilen malzemeler geliştirmeye ve kanatlar için etkili soğutma sistemleri tasarlamaya odaklanmışlardır. Malzeme teknolojisi ile elde edilebilecek iyileştirmelerde bazı sınırlamalar olsa da, soğutmanın önemi açıktır ve gaz türbinlerinde yüksek verimlilik sağlamak için kritik bir faktör olarak kabul edilmektedir. Bu amaçla, farklı malzemeler kullanılarak iki soğutma modeli geliştirilmiş ve kanatlardaki ısı transferi, SolidWorks paket programı ve Ansys 18.2 kullanılarak sayısal olarak analiz edilmiştir. Çalışma, titanyum karbür (TiC) ve üçüncü nesil tek kristal süper alaşım CMSX-10 malzemelerini ele almıştır. Kanat tasarımları, analiz sonuçlarına dayalı olarak önerilmiştir. Analiz, iyileştirilmiş modelin, termal özellikler açısından CMSX-10 malzemesi ile kullanıldığında daha iyi performans sergilediğini göstermiştir.

Anahtar Kelimeler: *Türbin kanadı, kanat soğutma, TiC, CMSX-10.*

1 Introduction

Gas turbine engines are mainly thermal engines consisting of a compressor, combustion chamber, and turbines. After fresh air enters through the intake port, the pressure in the compressor is increased, and a mixture is created by injecting fuel into the combustion chamber. High-pressure and high-temperature gases are obtained by burning the mixture in the combustion chamber. These gases pass to the turbine section, and by impacting the blades, they convert the heat energy into mechanical energy. Finally, the exhaust gases are thrown out, completing the cycle. Turbine technology converts fluid motion to useful work. It is a system in which many processes, such as taking atmospheric air, raising the gas temperature, and adding and burning the fuel at constant pressure, continue. A turbine blade is a component of a gas turbine that extracts energy from the high-temperature, high-pressure gases generated by the combustor. The turbine blades represent the limiting component of the gas turbine [1]. Turbine blade materials are generally preferred among nickel alloys, titanium alloys, and super alloys because they operate at high pressures and temperatures. Increasing the turbine rotor

*Corresponding author.

E-mail address: eng.sipahi@gmail.com (M. Sipahi)

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inlet temperature (RIT) has been shown to be an essential approach to increase the thrust performance of aero-gas turbines. [2, 3, 4, 6]. As the turbine inlet temperatures increase, the temperatures of the hot gases often exceed the melting points of the materials.

Fluid movement is used to create useful work using turbine technology. This includes many processes such as capturing atmospheric air. increasing air temperature Filling and burning fuel at constant pressure Turbine blades, which are generally made of nickel alloys titanium alloy or super alloy Considered a limiting element of gas turbines [1], turbine rotor inlet increasing temperature (RIT) has been identified as an important method for improving the thrust efficiency of air gas turbines. But when the temperature of the hot gas passing through the turbine blades increases. It often exceeds the melting point of the materials used in the blades. The development of heat-resistant materials and efficient cooling systems is increasingly important [2-5]. Gas turbine engines are one of the most widely used methods of to produce electricity and power aircraft in the 21st century, the use of heat energy generated during fuel combustion in the combustion chamber has greatly improved the efficiency of these engines. But gas turbine engines operate at very high temperatures, in excess of 1450 degrees Celsius. This can have a negative effect on the blades. This causes distortion and wear on the outer surface of the blade. To fix these problems and maintain the integrity of the blade Researchers are looking at new blade designs that combine metal alloys, blade shapes, and cooling.

Material selection and design procedures are critical in developing an efficient cooling system for turbine blades. To ensure the ability to withstand high pressure and temperature conditions. Researchers have conducted many theoretical and experimental studies on various types of alloys. used in turbine blades Alloys found to be suitable for turbine blades include titanium, chromium, nickel, and steel [7-8]. In this study, the researchers used a combination of single crystals and CMSX-10 super alloy to investigate potential improvements in blade cooling. By choosing these materials. The objective is to increase the durability and efficiency of turbine blades. especially in high temperature environments.

Ni-based single crystal superalloys are becoming increasingly important. To develop a gas turbine engine that meets ecological requirements to improve the thermodynamic efficiency of these engines New single crystal superalloys need to be developed that can withstand high turbine inlet temperatures.... The composition of the new generation superalloy has been modified to provide high resistance to corrosion, oxidation and creep in turbine blades. The amount of tungsten and molybdenum decreased. while the amount of cobalt, tantalum and aluminum increased. This change in the alloy structure is intended to harmonize the tension of the interface between phases A and B, resulting in improved turbine blade performance and durability.

CMSX-10 alloy is a high-performance material used in turbines and engine blades. Known for its high strength at high temperatures. Resistant to creep and fatigue Contains high amounts of rhenium and resistive elements. While the amount of chromium is relatively low, it happens. This alloy was initially developed for use in the air turbine industry. But it has also gained interest in industrial turbine applications because of its excellent long-term robustness at high temperatures. It is considered the third-generation single crystal casting material and has been approved for use in aircraft [14].

This barrier reduces heat transfer to the blade surface and protects the blade from hot air. Panel cooling is generally more effective at reducing the blade surface temperature compared to ventilation. However, its practical implementation is also more complicated and expensive. Therefore, a combination of internal film cooling methods is often used to achieve the optimum cooling efficiency in gas turbine blades. The cooling method used in a typical gas turbine engine depends on a number of factors, such as engine design, operating conditions, and the materials used in the blades.

Convection cooling involves the transfer of cool air through internal passages or tunnels within the blades. The cool air then spreads to the inner surface of the blade to remove the heat generated during operation. This method requires a larger number of blades to support the cooling path. This may affect the overall efficiency of the turbine engine. But it will provide more efficient cooling. and helps to increase the turbine inlet temperature [9].

Blade design is critical in achieving high efficiency and productivity in gas turbine engines. The blades control the flow of hot air to the turbine and convert kinetic energy into mechanical energy, which can be used to generate electricity or, as mentioned above, to power aircraft. The cutting can withstand high temperatures and pressures as well as harsh conditions. Engine operating environment Well-designed, manageable blades can increase engine reliability. Reduce maintenance costs and ultimately leads to better overall performance [4-6].

Development of new materials It is critical to meeting the increasing demand for high-performance, high-performance turbine engines. The use of super alloys has been found to be effective in withstanding high temperatures and pressures. and maintain mechanical properties Researchers have been searching for new superalloy compositions by adjusting the amounts of various alloying elements. appropriately to achieve the desired properties - resistance, high temperature creep and fatigue are also higher as compared to alloys [7].

Titanium carbide and Ni-based single-crystal superalloys were selected because of their excellent mechanical properties and thermal stability. The high melting point (3065°C) and low density ($4{\cdot}93$ g cc^{-1}) of Tic make Tic a potential material for high temperature applications [10]. The efficiency of gas turbines and jet engines has been improved. due to temperature. The capacity of Ni-based single crystal superalloy has been improved, which has an exceptionally high heat capacity [11]. Ni-based superalloys generally have 12 alloy compositions. The main component is Ni, which is used as the base material. It has an austenitic crystal lattice (FCC) structure [12].

The addition of other elements such as chromium, cobalt, aluminum, and titanium to the Ni-base super-alloys improves their mechanical properties, high-temperature strength, and resistance to thermal fatigue, creep, and oxidation [13]. These alloys also have excellent castability and weldability. This makes them suitable for a wide range of applications in the aerospace and energy industries. However, new and improved materials are being developed to meet the increasing demand for higher operating temperatures. And the increasingly critical operating conditions in modern gas turbine engines continue. The study you mentioned investigated the effect of microstructure on the creep performance of superalloy RR3010. The alloy was subjected to different hardening and aging rates. and the microstructure was characterized using scanning electron microscopy. Two different microstructures with different average gamma sizes (γ) were tested for creep at different temperatures and strains. The research results found that the granular structure has a significant impact on the creep performance at low temperatures. Where larger gamma size takes longer to break. But at a higher test temperature. The fine structure has a lesser effect on creep performance. Overall, the study provides valuable insights into the relationship between microstructure and creep behavior of super alloys, which is important for the design and optimization of high-performance materials for gas turbines and jet engines [13].

Efficient cooling of turbine blades is critical for their safe operation and to ensure their longevity. The use of internal and external cooling methods, such as film cooling, helps to maintain safe operating temperatures of the blades, which can exceed the limits allowed for turbine blade materials. However, as you mentioned, the cooling process can impact thermal efficiency, so the design of the cooling system and the fins should be optimized to balance cooling needs with performance goals. It is also important to consider the maximum surface temperature and temperature gradients of the fins in relation to the fin design and material used to prevent thermal stress that could lead to blade failure.

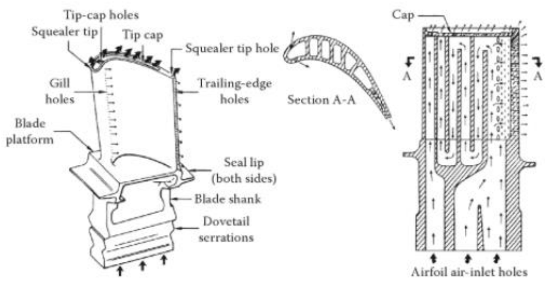

Figure 1. Design of fin with advanced cooling technology.

Figure 1 illustrates the design of the internal cooling channels in a GE CF6 turbofan engine's stage-1 high-pressure turbine rotor blade. Convective cooling, film cooling, rib turbulators, squealer-tip-cap cooling, and pin fins are all used to cool the blade. A combination of these cooling techniques is essential for optimum performance. and to ensure that the blades can work safely at high temperatures. Designing a thermal turbine blade is a very complex process that requires careful consideration of many factors, such as material properties. working environment and cooling efficiency [15, 16].

Accurate modeling of channels and paths in the blades is essential to ensure the most effective and efficient cooling. In addition to the shock from high turbulence. Other factors must also be considered, such as pressure differences and physical properties. By developing a comprehensive understanding of these phenomena and using advanced modeling techniques. Researchers and engineers can optimize turbine blade designs. Improved durability and performance.

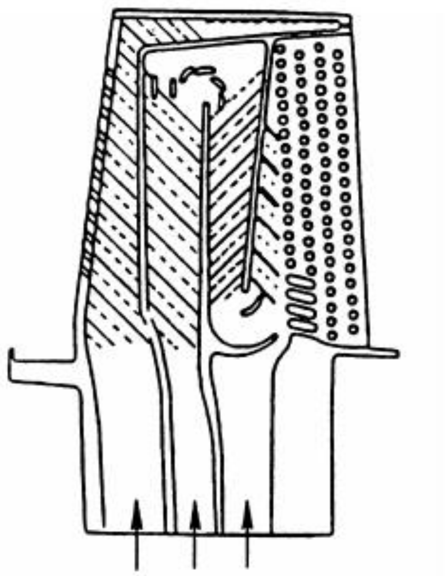

Figure 2 Fin internal cooling channel design using advanced cooling technology [5].

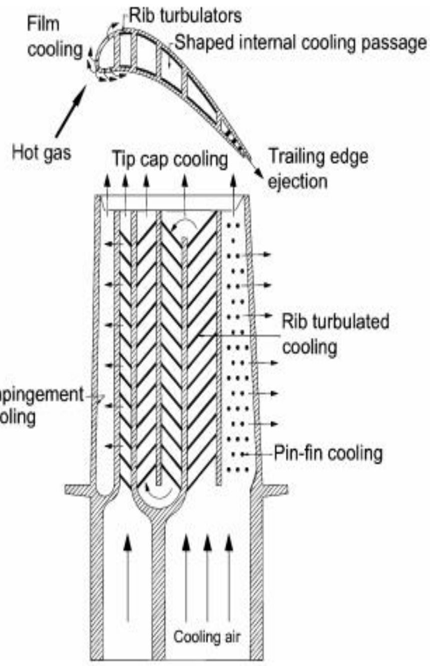

Figure 3 Schematic illustration of a multi-point air inlet fins [5].

Internal cooling channels are generally shown as short channels. square or squares with different aspect ratios Rib table geometry such as rib size, shape, distribution, angle of attack of flow. and the Reynolds number in the flow Its main function is to increase heat transfer in a rectangular cooling channel with a ribbed table. The heat transfer of the rib table by interrupting only the flow near the wall raises the level. As a result, the blade's internal cooling design adopts a reduction in the pressure drop caused by the rib table car.

2 Meterial Method

2.1 Internal Cooling

Internal cooling of the blades is achieved by forcing cool air from the air compressor through the internal cooling channel from the hub to the blade tips. The internal passages may be circular, oval, or spread over the entire surface of the blade. Such blade shape may deviate from the optimal aerodynamic blade profile. Conduction and convection are used to cool the blade; significantly hotter air leaves the blade tips and travels the length of the blade in the cooling passageways. Hollow blades with cores and internal cooling channels can be created. Cool air enters the front area like a jet. then move to the back [13, 14].

2.2 External Cooling

There are two methods of cooling the outside of a turbine blade. From the hub to the tip Cold air enters the interior corridor. during the ascent It can flow through a surface that crosses a number of small faces sloping on the surface. A film forms on the blade surface as a result of cool air escaping from these small holes, reducing heat transfer from the hot gas to the cutting metal. Except for cooling the cutting surface. [15]. SolidWorks is a popular CAD software used for 3D modeling of mechanical components and assemblies, while Ansys is a widely used simulation software for structural analysis, thermal analysis, fluid dynamics, and other engineering simulations. The use of these software packages allows for the creation of a detailed model of the turbine blade and the simulation of its behavior under different operating conditions. This can aid in the optimization of the blade's design and cooling system to improve its performance and durability.

2.3 Material Properties

In this study, we investigated the cooling efficiency of gas turbine blades using two distinct material types. The physical properties of the selected materials are provided in Table 1.

Table 1. Materials physical properties for turbine blade analysis.

Molecular Formula	Thermal conductivity (w/mk)	Poisson's Ratio	Density (kg/m^3)	Melting temperature (°c)	Yield strength (GPa)	Young' Modulus (GPa)	Thermal expansion (°c)
Titanium Ti	17	0,36	4620	1668	9,3	116	9,10 x 10 e-6
Titanium carbide Tic	21	0,18	4910	3160	20	497	7,60 x 10 e-6
Third-generation single crystal super alloys CMSX-10	26	0,21	8283	-	-	-	15,7 x 10 e-6

2.4 Blades Design

The turbine blade model was created in 3D using the SOLIDWORKS package program as seen in figures 4 and 5. Two different blades are modeled with internal cooling channels. and the generated model was transferred to Ansys program for further analysis. A lattice structure is created. And the simulation was edited using Ansys CFD, which is computational fluid dynamics software used to simulate fluid flow and heat transfer.

FEM is a numerical method used to solve partial differential equations by dividing the problem into smaller components or parts. The network model is then analyzed and simulated to predict system behavior and performance under various conditions. In the case of a model turbine blade, FEM is used to calculate the stress, strain, and temperature distribution across the blade under various operating conditions. The results from the FEM analysis are then used to optimize the design and improve the performance and reliability of the turbine blades [12]. These steps are typical for finite element analysis (FEA) using Ansys software, which is widely used for numerical simulations in the engineering industry. In the first step, a blade model is created in 3D CAD SolidWorks software with internal cooling channels. In the second step, the model is imported into Ansys, where meshes are created in the geometry model to break down the geometry into smaller, finite elements for numerical analysis. and select the mesh density according to the level of precision required for the results. In the third step Boundary conditions are applied to the model, such as temperature and pressure. and the equations of the system are solved to obtain results such as temperature distribution. heat flux and stress distribution.

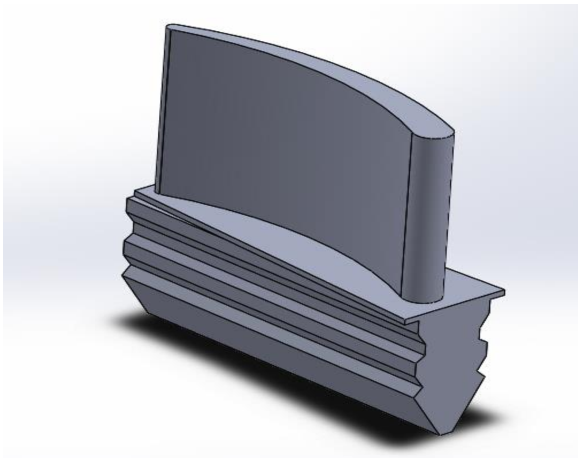

Figure 4. The main design of blade without cooling channels.

The analysis focuses only on the turbine blade cooling system. And the effect of air flowing in the propeller is not taken into account.

In computational fluid dynamics (CFD) simulation, the SIMPLE algorithm for pressure-velocity coupling is used. And the pressure interpolation model implied in the discrete solver is often used. In addition, the first order airflow model is commonly used to differentiate the control equations. The convergence parameters specified for the residuals determine the desired level of precision in the simulation results. Achieving residues based on these values is important to ensure a convergent and reliable solution.

These values indicate the level of accuracy and convergence of the numerical solutions obtained from the simulations. Residual energy represents the difference between the actual calculated kinetic energy in the system. While the kinetic turbulence and residual kinetic energy represent the difference between the actual calculated kinetic energy and the kinetic energy in the system, respectively. In this case, the residual energy of 10xe-6 and the residual kinetic energy/turbulent energy of 10xe-5 indicates that the simulation achieved a high level of accuracy and convergence.

This three-section turbine blade design is a common method used for internal cooling of gas turbine blades. The first section generally consists of a closed chamber through which cool air enters the blades. while the second section contains internal cooling channels. which is responsible for removing heat from the blades and finally, the third part is usually the exit area. This is where the cool air exits. Blades This three-piece design allows for a more efficient cooling system. Where cool air is distributed evenly and the heat transfer process is optimized.

To get better results, the fixed portion in the blade is discarded as shown in Figure 5 during the analysis process.

Unblocking the constant blocks during the analysis process can provide more precise and accurate results for areas of interest in the cooling path as shown in Figure 6. Because fixed blocks are not directly involved in the cooling process, they may impede ventilation and heat transfer to nearby cooling routes.

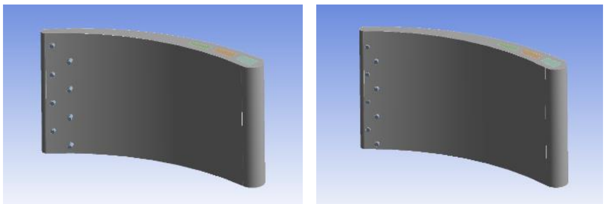

Figure 5. The design of blade with cooling channels for first and enhanced design.

Figure 6. The design of internal cooling channels for first and enhanced design.

3 Analysis and Result

The precise calculation of the heat transfer in turbine blades working at high pressures and temperatures requires a lot of time. The major parameters to increase gas turbine performance and engine life are generally acknowledged to be accurately measuring heat transfer and optimizing the operating temperatures of the fins in light of the acquired values. The development of high-speed computers has made it possible to perform precise calculations for heat transport analyses. The choice of appropriate turbulence models determines the primary challenges in forecasting. Meantime statistical models are used to build turbulence models. Meanwhile and variations in time are used to describe local velocities: U (local velocity) = u (time averaged) + u1 (fluctuating component)

Most turbulence models solve steady-state turbulence with the time averaging of seconds of fluctuating velocity components. Generally, turbulence kinetic energy is the sum of the turbulence energies k and is defined as [16];

Mean Flow Equations:

- Continuity:

$$\frac{\delta}{\delta x_i}(\rho U_i) = 0 \tag{17}$$

- Momentum Transport:

$$\frac{\delta}{\delta x_j}(\rho U_i U_j) = \frac{\delta P}{\delta x_i} + \frac{\delta}{\delta x_j}\left[\mu\left(\frac{\delta U_i}{\delta x_j} + \frac{\delta U_j}{\delta x_i}\right) - \rho\overline{u_i u_j}\right] \tag{18}$$

- Enthalpy:

$$\frac{\delta}{\delta x_j}(\rho U_i T) = \frac{\delta}{\delta x_j}\left[\frac{\mu}{Pr}\frac{\delta T}{\delta x_j} - \rho\overline{u_i t}\right] \tag{19}$$

- Zonal k-ε model: This consist of the high Re- k-ε in the fully turbulent core:

$$\frac{\delta}{\delta x_j}(\rho U_j k) = \frac{\delta}{\delta x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) - \frac{\delta k}{\delta x_j}\right] + P_k - \rho\varepsilon \tag{20}$$

Where, $P_k = -\rho\overline{u_i u_j}\left(\frac{\delta U_i}{\delta x_j}\right)$ (21)

$$\frac{\delta}{\delta x_j}(\rho U_j \varepsilon) = \frac{\delta}{\delta x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right) - \frac{\delta_\varepsilon}{\delta x_j}\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{22}$$

Analysis procedures were completed using the Ansys 18.2 program. Figure 7 shows the inlet and outlet domain information. For hot domain:Tinlet = 1200 K, and inlet velocity = 25 m/s.
For cold domain: Tinlet = 300 Kelvin and inlet velocity = 40 m/s

The total numbers of nodes and elements in first and enhanced designs are 417317, 2110027, 452253, 2266075 respectively as shown in Figure 8.

Figures 9 to 14 depict the variation of the resultant thermal gradient at the blade surface and internal cooling domain along the longitudinal distance.

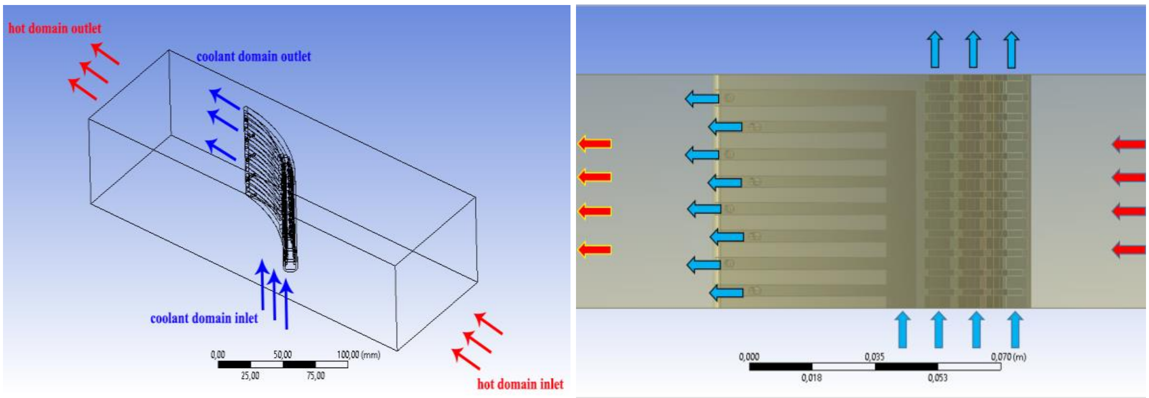

Figure 7. Information about simulation conditions.

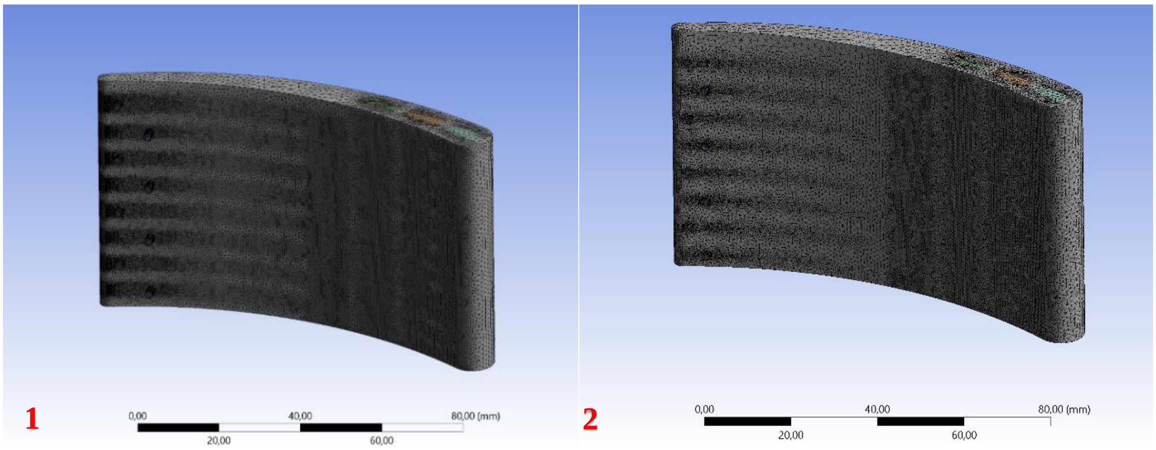

Figure 8. The generated finite element mesh used in the current research.

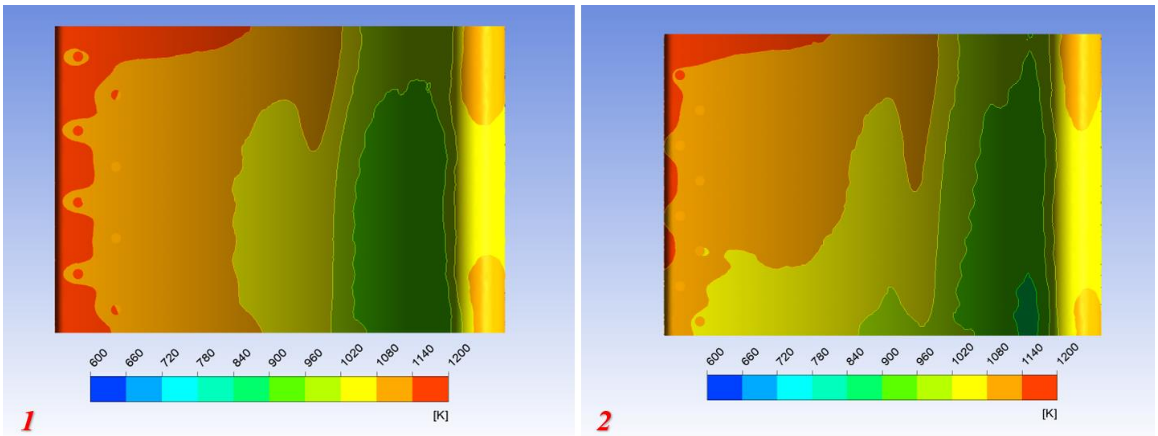

Figure 9. The variation of minimum and maximum temperature observed in blade for Titanium.

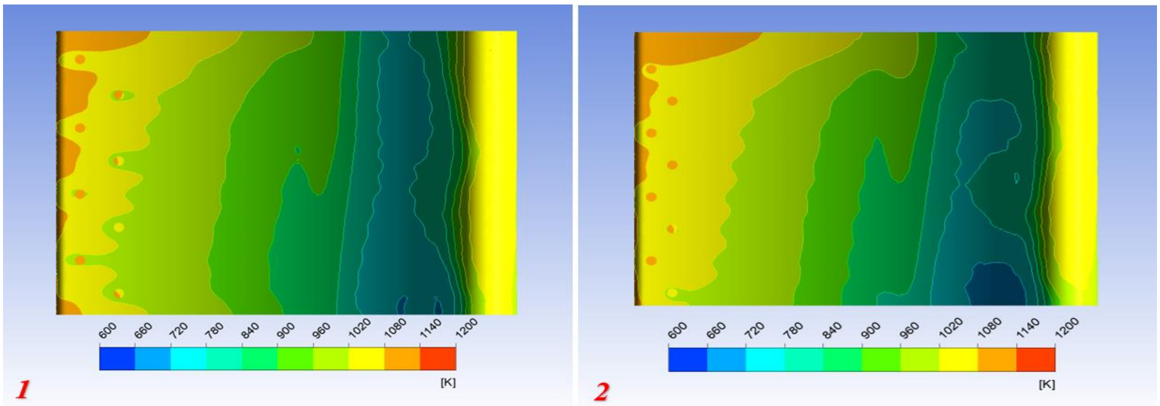

Figure 10. The variation of minimum and maximum temperature observed in blade for Titanium Carbide.

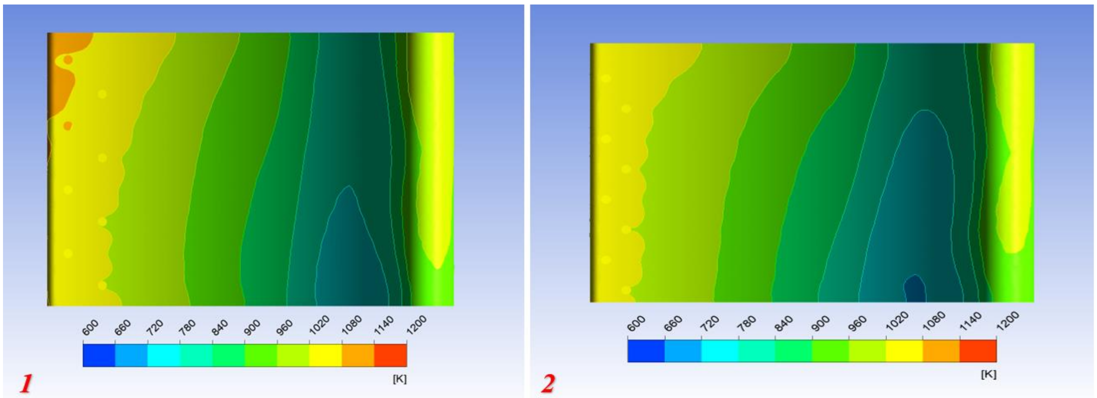

Figure 11. The variation of minimum and maximum temperature observed in blade for CMSX-10.

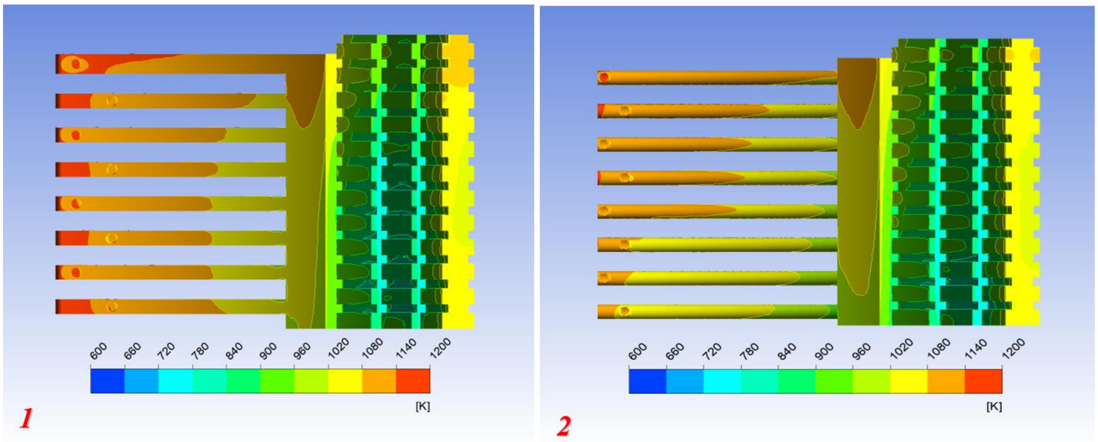

Figure 12. The variation of minimum and maximum temperature observed in cooling channels for Titanium.

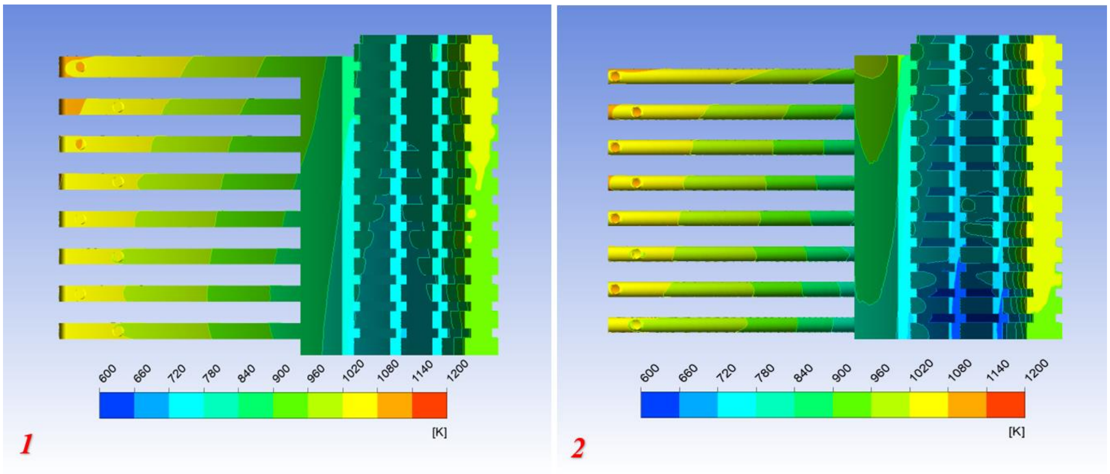

Figure 13. The variation of minimum and maximum temperature observed in cooling channels for Titanium Carbide.

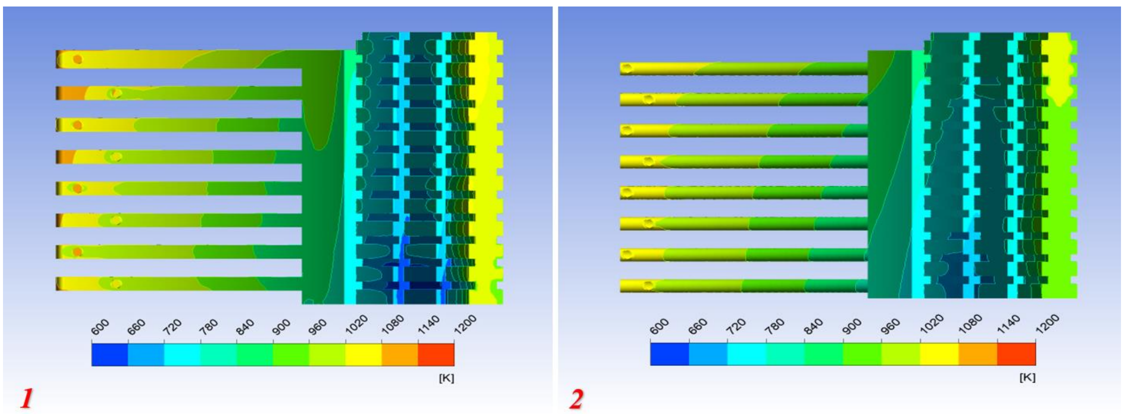

Figure 14. The variation of minimum and maximum temperature observed in cooling channels for CMSX-10.

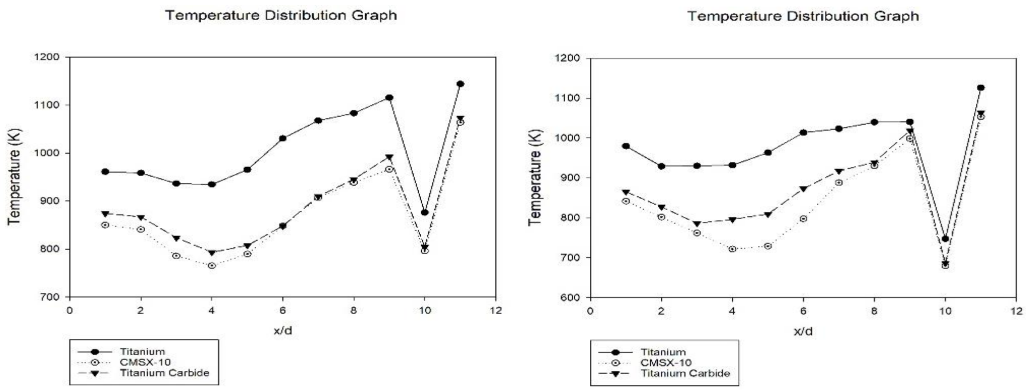

Figure 15. Temperature distribution for first and enhanced blade.

For the first design, a temperature increase is seen because the second and fifth points do not line up with the fin's cooling channels, as mentioned in figure 15.

- A rise in temperature is seen as the 6-7-8-9 points approach the narrow portion of the blade.
- The temperature drops because the 10th point falls on the edge of the film cooling hole.
- The last edge of the 11^{th}-point blade has the greatest temperature value.
- The temperature range for titanium material fluctuates between 900 and 1050 K on a regular basis.
- In the region of the cooling channels, the temperature distribution for titanium carbide and CMSX-10 falls by 750–850 K.

For the enhanced design,

- A temperature increase is seen because 2-3-4 points do not line up with the cooling channels of the blade.
- A rise in temperature is seen as the 6-7-8-9 points approach the narrow portion of the blade.
- The temperature drops because the 10^{th}-point falls on the edge of the film cooling hole.
- The last edge of the 11^{th}-point blade has the greatest temperature value. The temperature range for titanium fluctuates between 900 and 1000 K on a regular basis.

The temperature distribution in the cooling channels' region for titanium carbide and CMSX-10 reduces by 700–800 K.

Among the substances investigated, titanium carbide continually established lower top temperatures in both cooling designs, specifically inside the throat and trailing aspect regions, indicating advanced thermal resistance. While the first layout exhibited a steeper temperature gradient among the main and trailing edges, the enhanced design resulted in a greater uniform thermal distribution—maximum extensively for titanium carbide. However, whilst comparing average surface temperatures across the entire blade, CMSX-10 outperformed the opposite materials, accompanied by means of titanium carbide, whereas titanium exhibited the best ordinary temperatures.

4 Conclusion

Two different cooling models have been designed for a gas turbine engine's turbine blade. Additionally, both models have been numerically analyzed for maximum heat flux values of the gas turbine blade with three different materials. The use of circular-section channels in the obtained models has resulted in better cooling performance.

In addition to internal channels, film cooling, achieved through holes positioned on the channels, has also yielded better results compared to models with only internal channels. It was observed that there was an improvement in both internal-channel and film-cooling models depending on the material, but titanium carbide and single-crystal super-alloy showed better results. This indicates that improving the thermal conductivity properties of materials can provide advantages in cooling.

It is known that the thinness of the blade's trailing edges and the accumulation of heat are challenges. However, thanks to the created channel model and the positioning of film cooling holes, heat flux at the blade's trailing edge has increased. This can help reduce potential thermal damage.

The working temperature of the blade surfaces remained approximately around 900-1000 K. Considering that the materials can withstand working temperatures in the range of 1200-1300 K, the use of the cooling models can increase the temperature of exhaust gases from the combustion chamber, thereby improving the engine's performance.

As indicated by the numerical data of the study, the models obtained can be used in turbine blades, especially with single-crystal super-alloys and circular-section models with film cooling, to achieve better result.

From an engineering application perspective, these thermal characteristics directly affect the blade’s service lifestyles, efficiency, and preservation necessities. For instance, decrease most temperatures and smoother gradients, as seen in CMSX-10 and titanium carbide, are crucial for minimizing thermal fatigue, creep deformation, and oxidation, all of which are crucial failure modes in high-temperature environments which include aircraft engines and electricity-era generators.

CMSX-10’s superior thermal overall performance makes it in particular appropriate for applications in which reliability and persistence are prioritized. However, this material offers huge sensible obstacles: it's far steeplypriced, tough to device, and can require specialized casting or additive manufacturing techniques. These constraints can increase manufacturing prices and restriction its use to top rate, high-cost components.

Titanium carbide, imparting a stability among performance and cost, suggests promise for mild-duty turbines. However, its brittleness and potential oxidation troubles at extended temperatures may also require protective coatings or composite layering, including complexity to the layout.

Declaration

The authors declare that the ethics committee approval is not required for this study.

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