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Master Thesis

Domain	Sciences and Technologies
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By:
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Topic

Analysis of the thermal distribution within a gas turbine blade with a ceramic insulting coating and a nano-fluid coolant.

Defended Publicly in Front of the Jury Composed of

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Dedication

إلى أرواح الوطن ، الذين ضحوا بأرواحهم لكي نحيا بكرامة وحرية، لكم كل الحب والاحترام والامتنان.

إلى الشعب الفلسطيني المناضل والأرواح الفلسطينية، التي تقاوم الظلم وتناضل من أجل الحرية، نستلهم منكم الصمود والتحدي.

إلى ارواح المسلمين ، الذين غادرونا تاركين بصمات لا تُنسى في حياتنا، أرجو من الله أن يتغمدهم برحمته.

إلى دعاة الإسلام ديني والعربية لغتي والجزائر وطني، الذين يزرعون فينا القيم والمبادئ النبيلة، أنتم مصدر إلهامي وفخري.

إلى الوالدة والوالد، اللذين لم يدخرا جهداً في دعمي ومساندتي، لكم مني كل الحب والتقدير والامتنان.

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أتقدم بأسمى آيات الشكر والعرفان لله عز وجل على ما أنعم به عليّ من توفيق وتيسير لإتمام هذه المذكرة. لقد كان لفضل الله ومنته الدور الأكبر في كل خطوة خطوتها في هذا العمل.

بكل فخر وسرور أود أن أعبر عن خالص شكري وامتناني للأستاذ المؤطر [شوشان ناصر]، الذي لم يبخل علي بنصائحه القيمة وتوجيهاته السديدة، فكان دعمه وإرشاداته أساساً لنجاح هذا العمل. لقد كان مثالاً يحتذى به في التفاني والإخلاص، فله مني جزيل الشكر والامتنان.

كما أتوجه بجزيل الشكر والامتنان إلى لجنة التحكيم الموقرة، التي قدمت لي ملاحظاتها القيمة وتوجيهاتها البنّاءة، وساهمت بشكل كبير في تحسين جودة هذا العمل.

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General Introduction

The advancement of gas turbine technology is crucial for enhancing the efficiency and performance of various power generation and propulsion systems. One of the key challenges in improving gas turbine performance is managing the high temperatures experienced by turbine blades. Excessive temperatures can lead to material degradation, reduced efficiency, and ultimately, failure of the turbine components. To address these challenges, our thesis explores the innovative approach of integrating thermal barrier coatings (TBCs) and nanofluid cooling to improve the thermal management of gas turbine blades. Thermal barrier coatings are advanced material systems applied to the surface of turbine blades to provide thermal insulation. These coatings help to protect the underlying metal substrate from extreme temperatures, thus extending the lifespan of the blades and enhancing the overall efficiency of the turbine. TBCs are typically made from ceramic materials, which possess low thermal conductivity and high thermal resistance, making them ideal for high-temperature applications.

Nanofluids, which are fluids containing nanometer-sized particles, offer superior thermal properties compared to conventional cooling fluids. The inclusion of nanoparticles can significantly enhance the thermal conductivity and heat transfer capabilities of the coolant, allowing for more efficient cooling of turbine blades. This advanced cooling technique is particularly effective in high-temperature environments where traditional cooling methods may fall short.

The primary objective of this thesis is to evaluate the effectiveness of combining thermal barrier coatings with nanofluid cooling in reducing the temperature distribution across gas turbine blades. By utilizing a Computational Fluid Dynamics (CFD) module in ANSYS, we aim to simulate and analyze the thermal performance of turbine blades under these enhanced cooling techniques.

The simulation results revealed a significant decrease in the temperature distribution across the turbine blade when using the combination of thermal barrier coatings and nanofluid cooling. The integrated approach showed a substantial improvement in thermal management, with the temperature of the blade being considerably lower compared to conventional cooling methods. This reduction in temperature not only enhances the efficiency and performance of the gas turbine but also contributes to the longevity and reliability of the turbine components.

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Chapter I

Gas turbine Overview

1 Introduction

The gas turbine is a combustion engine known for providing a lean, reliable, and efficient method for generating substantial energy, a capability intricately tied to its physical attributes, specifically size and weight.

The size and weight of a gas turbine are acknowledged as critical factors influencing its energy output, with larger and heavier turbines generally possessing the potential for greater energy production across diverse applications, from industrial power plants to aviation propulsion systems [1].

The fundamental components of a gas turbine typically include a compressor, combustion chamber, and turbine. The turbine inlet gas temperature (TIT) is a crucial parameter significantly impacting turbine performance and efficiency. Higher turbine inlet gas temperatures generally result in improved efficiency due to a heightened temperature difference between combustion gases and surroundings, known as the temperature ratio, a key factor in determining the efficiency of the thermodynamic cycle.

However, there exists an upper limit to the inlet temperature that a gas turbine can withstand, primarily due to material constraints. Excessive temperatures can lead to issues such as blade fatigue, corrosion, overheating, high vibration and resonance, thermal stress, material degradation, and reduced component life. Engineers meticulously design gas turbines to operate within specified temperature limits, striking a balance between efficiency and the longevity of turbine components [2].

In response to these challenges, ongoing research and technological advancements aimed at addressing inlet temperature issues have been pivotal in enhancing overall gas turbine performance.

The past two decades have witnessed substantial growth and advancements in gas turbine technology, marking a transformative period in the field. Key developments, spearheaded by the growth of materials technology, coupled with the evolution of new coatings and cooling schemes, have played an instrumental role in advancing the capabilities of various industries [1].

Embracing these advancements not only contributes to improved efficiency and performance but also enables the creation of more sustainable and technologically advanced solutions.

1.1 Purpose and research questions

To investigate the impact of thermal barrier coatings (TBCs) and nano-fluid cooling on the thermal performance and durability of gas turbine blades. By employing computational fluid dynamics (CFD) simulations with Ansys software.
In this thesis, the investigation focused oninvestigate the temperature distribution in a thermal barrier coating (TBC) system applied to gas turbine blades when subjected to cooling with a nano-fluid. By focusing on specific questions :

- How does the combination of thermal barrier coatings (TBC) and nanofluid coolant affect the thermal behavior of gas turbine blades?
- What are the comparative advantages of using nano-fluid coolants over conventional coolants in terms of temperature reduction and thermal stress minimization?
- How can innovative strategies for managing thermal loads contribute to the advancement of turbine technology and improve overall efficiency and reliability?

2 Gas turbine engines

A gas turbine, also known as a combustion turbine, is a type of internal combustion engine that converts energy from fuel into mechanical energy through the combustion (burning) of the fuel.In a gas turbine [3].

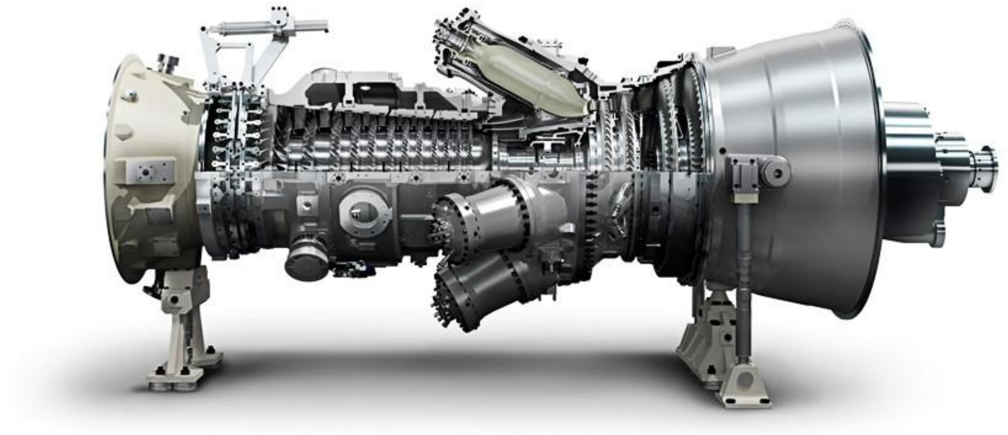


Figure I.1: SGT 750 Gas turbine [4].

The basic components of a gas turbine include: Compressor, Combustion Chamber, Turbine, Exhaust.

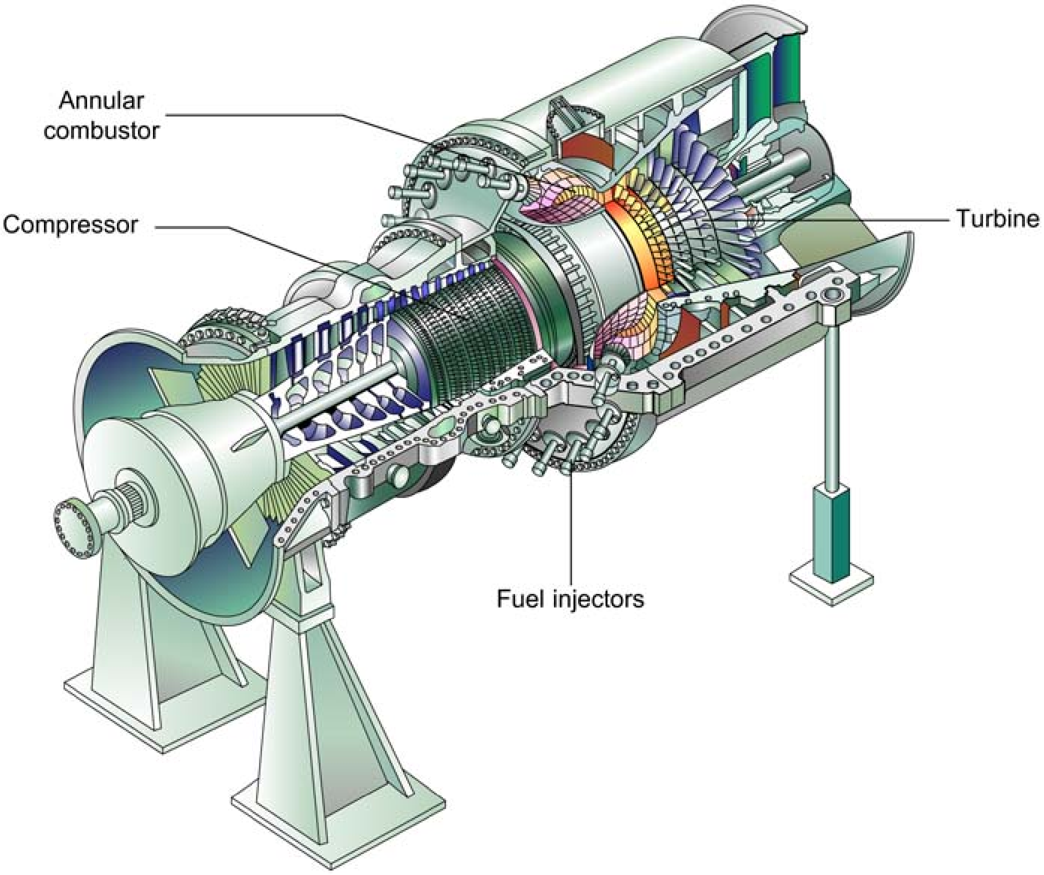


Figure I.2: Gas turbine components(Siemen's V94.2) [1].

2.1 Operation principle

Air is drawn into the engine and compressed to high pressures by a series of rotating blades in the compressor. After that, the compressed air is mixed with fuel, and the resulting mixture is ignited. This combustion process produces high-pressure and high-temperature exhaust gases that pass through a turbine. The compressor and turbine are connected by a shaft, which transfers the mechanical energy generated by the turbine to drive the compressor [3].

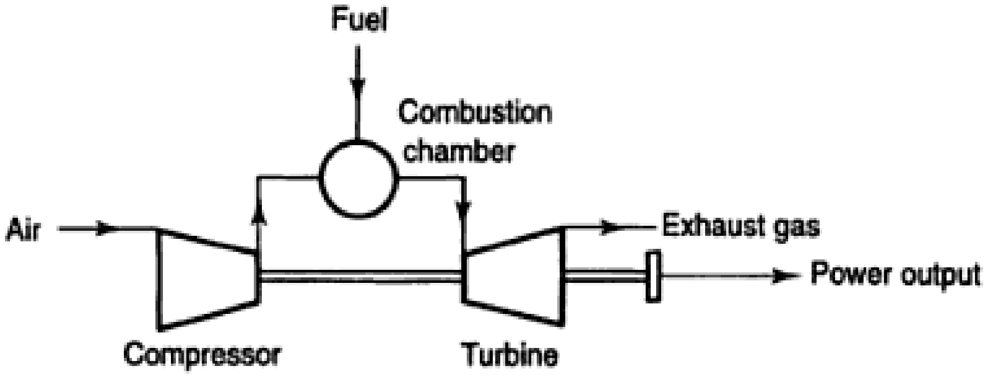


Figure I.3: Simple Gas turbine Stage [3

2.2 Gas turbine sections

2.2.1 Compressor Section

The compressor section is a crucial component of a gas turbine engine. Its primary function is to compress incoming air before it enters the combustion chamber. This compression raises the pressure and temperature of the air, making it suitable for efficient combustion and power generation.

The compressor section typically consists of one or more stages of compressors, and there are two main types: axial and centrifugal [1].

- **Axial Compressor :**

  In an axial compressor, the air flows parallel to the axis of rotation. It consists of multiple sets of rotating and stationary blades (rotor and stator). As the rotor blades spin, they accelerate the air and pass it to the next set of stationary blades, where further compression occurs.
  This process is repeated through several stages until the desired pressure is achieved [1].

- **Centrifugal Compressor :**

In a centrifugal compressor, air is drawn into the center of a spinning impeller, and centrifugal force throws the air outward. The diffuser then converts the high-velocity air into high-pressure air. While axial compressors are common in aircraft engines, centrifugal compressors are often used in industrial gas turbines [1].

- **Diffuser :**

  After compression, the air passes through a diffuser, which is a section that slows down the high-velocity air and further increases its pressure.
  Both the rotor and stator sections of a gas turbine axial compressor consist of multiple blades. These blades work together in stages to compress the incoming air before it enters the combustion chamber. Where fuel is added and ignited, leading to the production of high-temperature, high-pressure gases that drive the turbine section. Efficient compression in the compressor section is essential for the overall performance and efficiency of the gas turbine engine. The design and operation of the compressor are critical factors in achieving optimal power output and fuel efficiency [1].

2.2.2 Combustion Section

The combustion section, also known as the combustion chamber, The combustion section of a gas turbine is a crucial component where fuel undergoes controlled burning to produce high-energy exhaust gases. Fuel, either liquid or gaseous, is injected into the combustion chamber where it mixes with compressed air from the compressor section. high-pressure gases that drive the turbine section of the engine [5].

2.2.3 Turbine Section

The turbine section of a gas turbine engine is a critical component that converting the high-temperature, high-pressure gas flow from the

combustion chamber into mechanical energy.
The turbine assembly in a gas turbine engine typically consists of two fundamental elements: turbine inlet guide vanes (TIGVs) and turbine blades.[Figure I.4 and I.5] [6].

Figure I.4: Turbine inlet guide vanes (TIGVs) [6].

Figure I.5: Turbine blades [6].

This process involves expanding and accelerating the exhaust gases through a series of turbine blades mounted on a shaft. As the gases flow over the blades, they transfer their kinetic energy to the turbine blades, causing them to rotate. This rotational motion is then used to drive the compressor section at the front of the engine via a shaft, which in turn compresses incoming air, creating a continuous cycle of air intake, combustion, and power generation [6].

2.3 Heat transfer and fluid flows

Heat transfer in gas turbines is a critical aspect of their operation, influencing performance, efficiency, and durability.

The investigation of heat transfer phenomena in airfoils and fluid flows is of paramount importance in numerous engineering disciplines. This is due to hot gas expansion and the velocity. As the high-pressure, hot gas expands, it undergoes a rapid transformation in velocity, leading to significant changes in flow characteristics and heat transfer mechanisms.

In this context, three different modes can generally transport heat, conduction, convection and radiation.

2.3.1 Conduction

Conduction indeed refers to the transfer of heat from regions of higher temperature to regions of lower temperature within a material or between different materials in direct contact, primarily through direct molecular contact.

The rate of heat transfer through conduction depends on two primary factors: the thermal conductivity of the material and the temperature difference across the material [7], and is given by Fourier's law as:

$$\dot{q} = -kA\frac{dT}{dx} \qquad \text{(W)} \tag{I.1}$$

Where:

- q˙ is the rate of heat transfer(in watts),
- k is the thermal conductivity of the material(in watts per meter per degree Celsius),
- A is the cross-sectional area through which heat is transferred(in square meters),
- dT/dx is the temperature gradient along the direction of heat transfer.

2.3.2 Convection

The movement of High-temperature gases alongside cooling flow surface Generates a transfer of heat to the surface, a phenomenon whose rate is contingent upon various factors such as the fluid's properties and the nature of its flow, be it natural convection, laminar, or turbulent. To comprehend and quantify this mode of heat exchange, Prandtl, in 1904, introduced the boundary layer concept, postulating a hypothetical layer near the surface where the entirety of heat transfer resistance is concentrated. This conceptualization facilitated significant simplifications in analysis and was widely embraced by researchers, although there were dissenting voices, notably Adiutori (1974) [7].

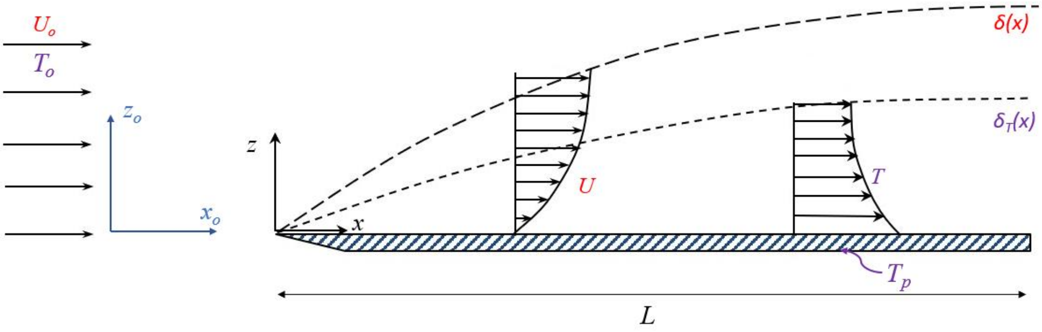


Figure I.6: Boundary layer over a flat plate.

The general equation for heat transfer through convection can be expressed using Newton's Law of Cooling, which relates the rate of heat transfer to the temperature difference between the surface and the surrounding fluid. It is represented as:

$$TotalRadiantFlux = h \cdot A \cdot \Delta T \qquad (\mathrm{W}) \tag{I.2}$$

Where:

- $\dot{Q}$ is the rate of heat transfer (W or J/s),
- h is the convective heat transfer coefficient ($\mathrm{W/(m^2 \cdot K)}$),
- A is the surface area (m^2),
- ΔT is the temperature difference (°C or K),

2.3.3 Radiation

Heat transfer by electromagnetic radiation is indeed a fundamental principle in thermodynamics and is governed by the laws of radiation. All materials emit, absorb, and transmit electromagnetic radiation to varying degrees, with these properties strongly influenced by the material's temperature. The absorptivity of a material refers to its ability to absorb radiation. It is represented by the symbol "α" and typically ranges from 0 to 1. A perfect absorber, known as a blackbody, has an absorptivity of 1 [7].

The relationship between temperature, radiation emission, absorption, and transmission is described by principles such as Stefan-Boltzmann law :

$$P = \sigma A T^4 \tag{I.3}$$

where:

- P is the total power radiated,
- σ is the Stefan-Boltzmann constant ($\sigma \approx 5.67 \times 10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$),
- A is the surface area,
- T is the absolute temperature in Kelvin.

3 The used methods to Increase the performance of a gas turbine

Enhancing the performance of gas turbines involves employing various methods to improve efficiency, power output, and reliability.

Inlet air cooling is one such method utilized to boost performance and efficiency by lowering the temperature of air entering the compressor stage [8].

This reduction in the inlet air temperature aims to increase the air density, enabling the gas turbine to generate more power without a proportional increase in fuel consumption. Studies have shown that for every 5°C decrease in inlet air temperature, the system's thermal efficiency increases by approximately 2–5%, indicating that cooler inlet air enhances the energy conversion process and leads to more efficient fuel utilization [9].

3.1 Evaporative cooler

One common approach to inlet air cooling is evaporative cooling, which involves reducing the temperature of ambient air entering the gas turbine's compressor.

This process increases air density, allowing the compressor to draw in more air molecules per unit volume, resulting in higher mass flow rates and improved turbine performance [10].

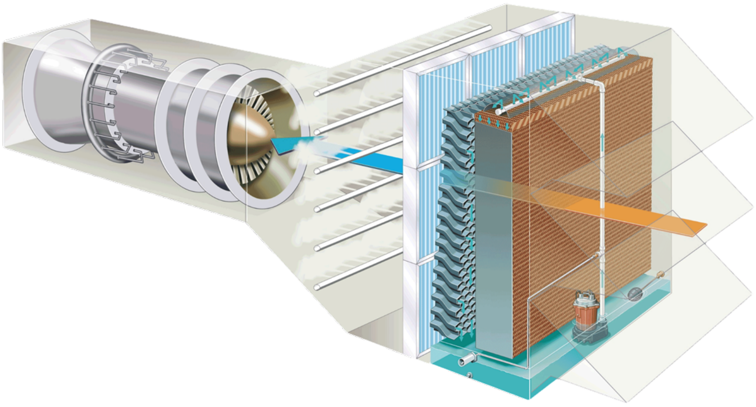


Figure I.7: Evaporative cooling gas turbine [11].

3.2 Absorption cooling

Absorption cooling, a thermally driven process predicated on the principles of absorption, offers a compelling avenue for enhancing the performance of gas turbines within industrial settings. Unlike traditional vapor compression refrigeration systems reliant on mechanical compressors, absorption cooling systems leverage heat sources to facilitate refrigerant cycling, thereby producing chilled water or air. This process typically involves components such as absorbers, generators, pumps, and evaporators. The utilization of waste heat, often sourced from gas turbine exhaust or other industrial processes, is pivotal in driving the absorption process.

By harnessing this waste heat, absorption cooling systems can supplement gas turbine operations, particularly by cooling inlet air or critical turbine components [12].

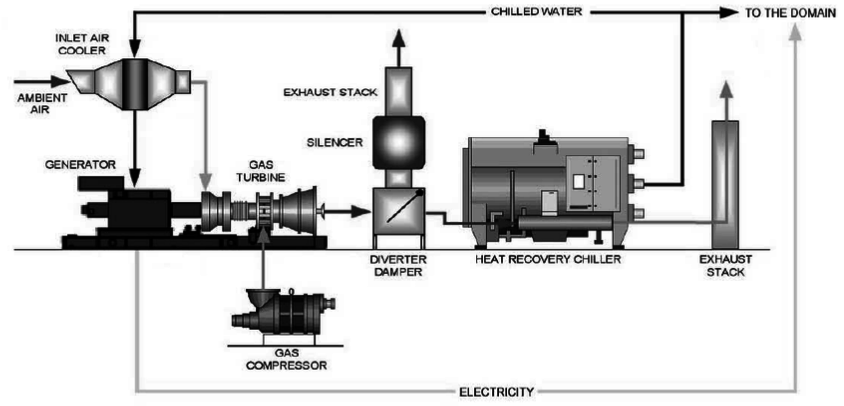


Figure I.8: Absorption Cooling for gas turbine [13].

3.3 Mechanical Refrigeration

Mechanical refrigeration operates within the framework of thermally driven cooling processes but differs fundamentally in its operational mechanism. This systems can be classified into two main categories based on how they transfer heat: direct and indirect refrigeration systems.

3.3.1 Direct cooling

In direct refrigeration systems, the cooling effect is achieved by directly circulating the refrigerant through the space or substance to be cooled. The refrigerant absorbs heat from the surrounding environment, undergoes phase changes (e.g., from liquid to vapor) in the process, and then returns to the compressor to begin the cycle anew. Direct refrigeration systems are commonly used in applications such as residential air conditioning units, refrigerators, and freezers, where the refrigerant directly cools the air or objects within the enclosed space [14].

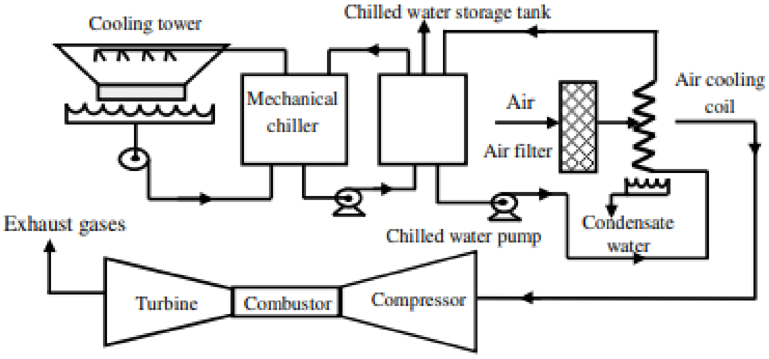


Figure I.9: Main components of the direct cooling system [15].

3.3.2 Indirect cooling

Indirect cooling, often implemented through chillers, is a widely employed method in industrial and commercial settings to achieve precise and efficient temperature control for various processes and applications. Unlike direct cooling methods such as evaporative cooling, which directly cools the air or fluid passing through the cooling medium, indirect cooling relies on a heat transfer fluid to remove heat from the target environment. Indirect cooling systems, commonly facilitated by chillers, offer a sophisticated approach to temperature management in industrial and commercial environments, encompassing applications ranging from process cooling to air conditioning.

These systems operate on the principle of heat exchange, utilizing a heat transfer fluid, typically water or a specialized refrigerant, to absorb heat from the target environment. Within the context of gas turbine performance enhancement, indirect cooling assumes significance primarily in the form of inlet air cooling. By employing chillers to lower the temperature of the ambient air entering the gas turbine compressor, the air density is increased, leading to enhanced turbine performance and power output. Additionally, indirect cooling systems are pivotal in maintaining optimal operating conditions for critical turbine components, such as blade cooling systems, thereby ensuring operational efficiency and prolonging equipment lifespan [16]. Main components of the indirect cooling system was showed in figure I.10 [15]

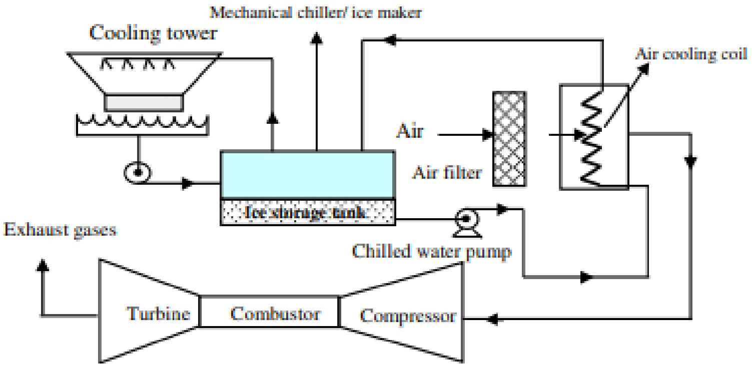


Figure I.10: Main components of the indirect cooling system.

3.3.3 Intercooler (Intermediate cooling of the compressor)

Intermediate cooling of the compressor, a crucial aspect in gas turbine design and operation, involves the strategic placement of cooling systems to mitigate temperature rise within the compressor stages. This intermediate cooling mechanism is positioned between the high-pressure and low-pressure compressor stages to address thermal stress and optimize turbine performance. By employing various cooling techniques, such as film cooling, convective cooling, or bleed air cooling, excessive heat generation within the compressor is alleviated, thereby enhancing efficiency and extending component lifespan.

Intermediate cooling serves multifaceted objectives, including reducing compressor blade temperatures, preventing thermal degradation of materials, and mitigating compressor stall risks. Moreover, by maintaining optimal operating conditions and preserving aerodynamic integrity, intermediate cooling contributes to overall gas turbine performance enhancement, ensuring reliable and efficient power generation across diverse industrial applications [17].

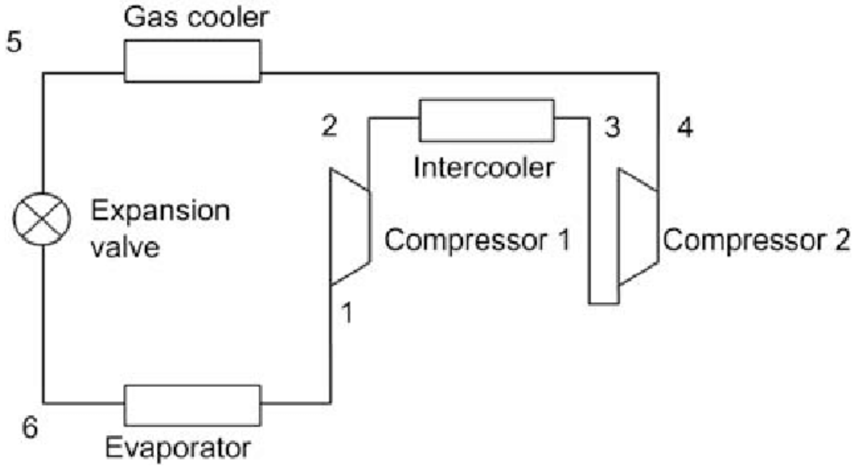


Figure I.11: Installation with intermediate cooling of the compressor [18].

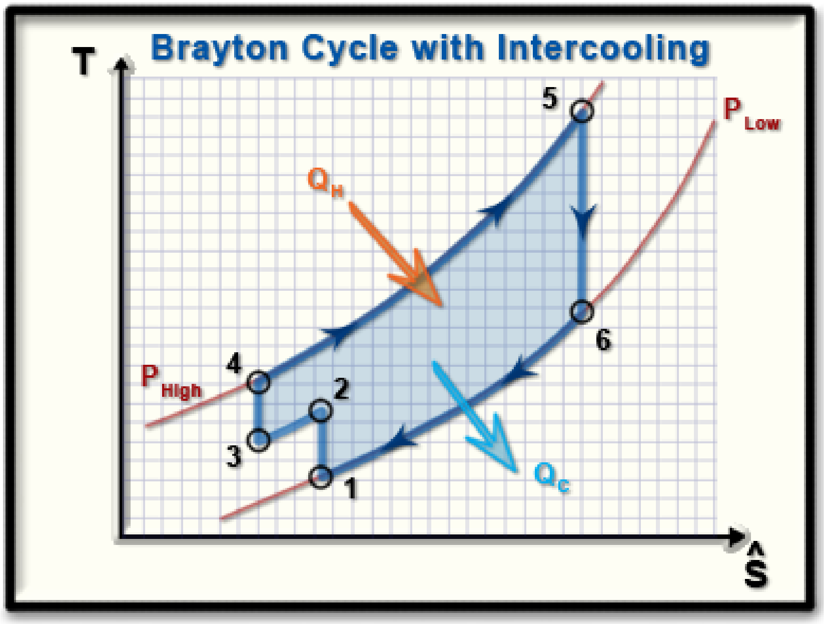


Figure I.12: Brayton Cycle with an inter-cooler [19].

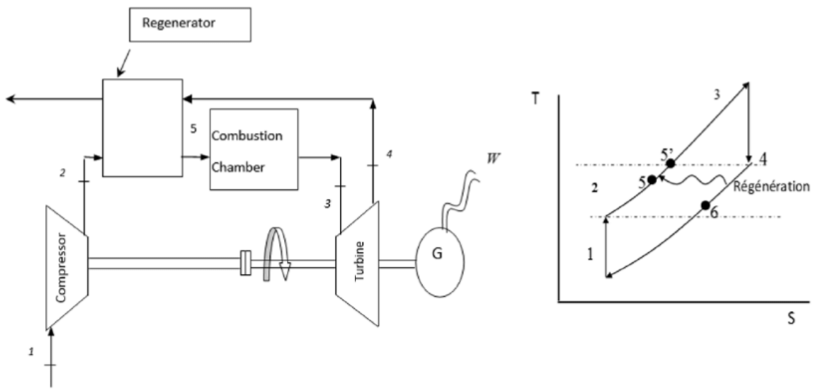
3.3.4 Regeneration (recovery cycle)

Regeneration is a process that recovers waste heat from the turbine exhaust and utilizes it to preheat the air entering the combustion chamber or to generate steam for additional power generation.

This process helps improve the overall efficiency of the gas turbine system by making more effective use of the heat energy that would otherwise be lost. There are two main types of regeneration commonly employed in gas turbine systems:

- **Air Preheating:**
  In this type of regeneration, the waste heat from the turbine exhaust is transferred to the incoming combustion air before it enters the combustion chamber. By preheating the air, less fuel is required to reach the desired temperature for combustion, resulting in fuel savings and increased overall thermal efficiency.

- **Heat Recovery Steam Generation (HRSG):**
  In HRSG systems, the waste heat from the turbine exhaust is used to generate steam. This steam can then be used to drive a steam turbine for additional power generation, or it can be utilized for other industrial processes requiring steam. HRSG systems are commonly employed in combined cycle power plants, where both gas and steam turbines are used to generate electricity, maximizing overall efficiency [20].



(a) (b)

Figure I.13: Regenerative-gas-turbine-cycle-T/S-diagram-of-regenerative [21].

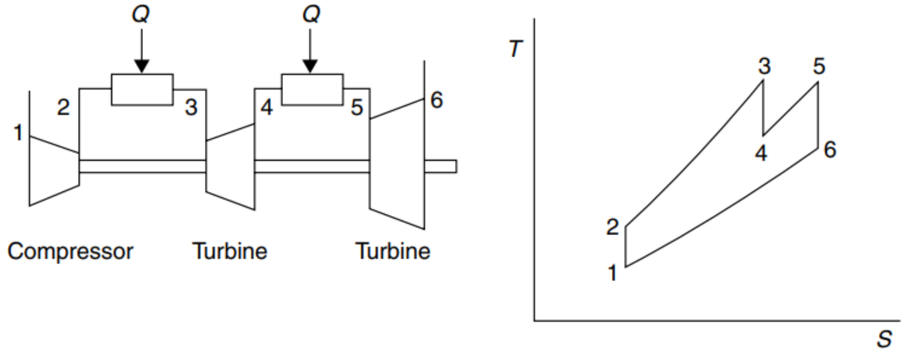


Figure I.14: Installation with turbine reheating [22].

3.3.5 Inter-turbine expansion heater

The inter-turbine expansion heater is a device used in gas turbine engines to improve the efficiency of the engine. It works by extracting heat from the exhaust gases between the high-pressure and low-pressure turbine stages and using that heat to preheat the air entering the combustion chamber. The key function of the inter-turbine expansion heater is to increase the temperature of the air entering the combustion chamber.

This allows the engine to operate at a higher overall temperature, which in turn increases the thermal efficiency of the engine. By preheating the air, the inter-turbine expansion heater reduces the amount of fuel required to achieve the desired combustion temperature, resulting in improved fuel efficiency. In this system, the hot exhaust gases from the gas turbine pass through a heat exchanger where they transfer heat to the working fluid. This causes the working fluid to vaporize and expand, driving a turbine connected to a generator to produce additional electricity.

By extracting more energy from the waste heat of the gas turbine exhaust, ITEH systems increase the overall efficiency of the combined cycle power plant [23] .

4 Turbine stresses

4.1 Thermal Stress

Thermal stress is a critical factor influencing the performance and longevity of components in high-temperature environments. Thermal stress arises due to the stark temperature differentials experienced by the blade during operation, particularly in the hot gas path. As hot combustion gases pass over the turbine blades, they rapidly heat up, causing thermal expansion.

However, as the blades are typically anchored at their root, this expansion leads to significant thermal stresses within the material. Such stresses can result in various failure mechanisms, including creep, fatigue, and ultimately fracture.

The severity of thermal stress is influenced by several factors, including operating temperature, cooling mechanisms employed, material properties, and design considerations. Effective thermal management strategies, such as advanced cooling techniques and materials with high-temperature capabilities, are essential for mitigating thermal stress and ensuring the reliability and durability of gas turbine blades in demanding operating conditions [24].

4.2 Creep

Creep is a gradual deformation phenomenon that occurs in gas turbine blades subjected to high temperatures and mechanical stresses over extended periods of operation.

It is particularly prevalent in blades operating in the hot sections of gas turbines, where temperatures can exceed the material's creep threshold. Creep results from the combined effects of high temperature and mechanical loading, causing the blade material to slowly deform over time, even under relatively low stresses. This deformation can lead to dimensional changes, distortion, and ultimately, failure of the blade [25].

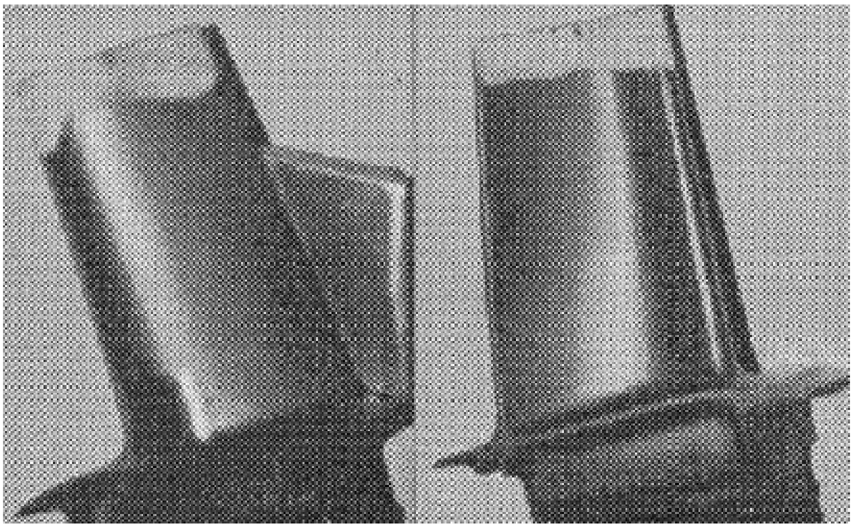


Figure I.15: Fissures of the turbine blade caused by creep [25].

4.3 Fatigue failure

Gas turbine blade fatigue failure is a significant concern, with repeated loading during operation leading to fatigue cracks and potential failure mechanisms.

Factors contributing to fatigue failure include the large centrifugal force from high rotational speed and temperature changes, which can accelerate thermal pressure distribution and cause fatigue.

Additionally, impurities accumulating on the blade surface can damage the protective oxide layer, accelerating oxidation and corrosion, ultimately reducing material thickness and fatigue strength.

Effective monitoring and analysis of technical causes,including design factors, environmental conditions, fuel cleanliness, and maintenance history, are crucial for preventing fatigue-related failures in gas turbine blades [9].

4.4 Oxidation and Corrosion

Gas turbine blades face corrosion and oxidation challenges due to harsh environments like high temperatures, humidity, and pollutants.

Corrosion types include oxidation, hot corrosion, and crevice corrosion, each posing risks to blade integrity. Nickel-based superalloys are often chosen for their resistance, but they can still degrade. Environmental factors and operational conditions like temperature and fuel composition exacerbate corrosion. Regular maintenance, inspections, and monitoring systems are vital for detecting early corrosion signs. Optimizing blade design with airflow, cooling, and coatings helps mitigate risks [25].

4.5 Erosion Failure

Erosion failure in gas turbine blades occurs when abrasive particles in the airflow wear away the blade material over time. These particles can originate from various sources, including dust, sand, and debris in the air.

High-velocity gases and turbulent airflow exacerbate erosion, particularly in regions where airflow velocities are highest, such as near the leading edge of the blade.

Erosion can result in loss of blade material, leading to changes in aerodynamic performance and structural integrity. Protective coatings and materials with enhanced erosion resistance are employed to mitigate erosion effects. Regular inspections and maintenance are essential for detecting and addressing erosion damage to ensure continued turbine efficiency and reliability.

5 Blade's Overview

The evolution of blade , running parallel to the development of isolated airfoils, has been a cornerstone in the advancement of both compressor and turbine sections, intricately linked with the progress of aviation and gas turbine technology. This evolution significantly contributes to the overall efficiency of the system.

Throughout history, the development of blade design has been closely intertwined with broader advancements in aerodynamics and gas turbine technology. Early pioneers in aerodynamics, such as George Cayley [26] and Otto Lilienthal "laid the foundational principles in the 19Th century"[27].

Researchers have focused on studying isolated airfoils to gain insights into intricate flow dynamics. The post-World War II era witnessed a surge in research and development, driven by the demand for more powerful and efficient aircraft engines. Advances in materials, manufacturing techniques, and computational tools have propelled blade design to new heights. The advent of computational tools in the 1970s, including numerical simulations and computational fluid dynamics (CFD) such as RH Liebeck [28], significantly accelerated the understanding of complex airflow interactions around airfoils.

Modern advances, characterized by collaboration between industry and research institutions, continue to refine and optimize blade efficiency, considering factors like aerodynamic efficiency and structural integrity.

This multifaceted progress has contributed to a substantial increase in the performance and efficiency of gas turbines and propelled a significant growth in gas turbine technology, driven primarily by advancements in materials technology, the development of new coatings, innovative cooling schemes, and the expansion of combined-cycle power plants. These technological strides have significantly enhanced the performance, efficiency, and environmental sustainability of gas turbines. The evolution of materials technology enabling turbines to operate at higher temperatures and pressures, they increasing overall efficiency[29].

Additionally, the implementation of cutting-edge coatings on turbine components has improved durability, corrosion resistance, and thermal protection, extending the lifespan of critical parts. Innovative cooling schemes, such as advanced air and film cooling techniques, have been pivotal in maintaining optimal operating temperatures and preventing component degradation.

This multifaceted progress underscores the dynamic nature of gas turbine technology, propelled by continuous research, development, and integration of advanced engineering solutions.

Turbine blades are often made from advanced materials that can withstand extreme environments while maintaining structural integrity such as high temperatures, high rotational speeds, and corrosive environments.
As a result, turbine blades are often made from advanced materials that can withstand extreme environments while maintaining structural integrity such as high temperatures, high rotational speeds, and corrosive environments,

While the materials used for gas turbine blades need to possess specific properties to withstand these harsh conditions.

5.1 Advanced Materials:

In the 1960s and 1970s, the development of gas turbine blades were typically made from steel alloys. While effective, these blades faced limitations in terms of their ability to withstand high temperatures and maintain structural integrity under the demanding conditions of turbine operation[30].
The breakthrough came with the introduction of nickel-based superalloys

in the mid-20th century. These alloys, incorporating elements like nickel, cobalt, chromium, and others, exhibited exceptional high-temperature strength, corrosion resistance, and durability.
Nickel-based superalloys quickly became the material of choice for hot-section components [31], including turbine blades.

Alongside material advancements, cooling techniques underwent a significant evolution. Innovations such as film cooling, internal cooling channels [32], and thermal barrier coatings (TBCs) emerged to mitigate the effects of high temperatures on blade surfaces [33].
This continuous pursuit of innovation underscores the dynamic nature of gas turbine blade technology, driving advancements in aerospace, power generation, and other industrial sectors.

5.2 Turbine Inlet Temperature (TIT):

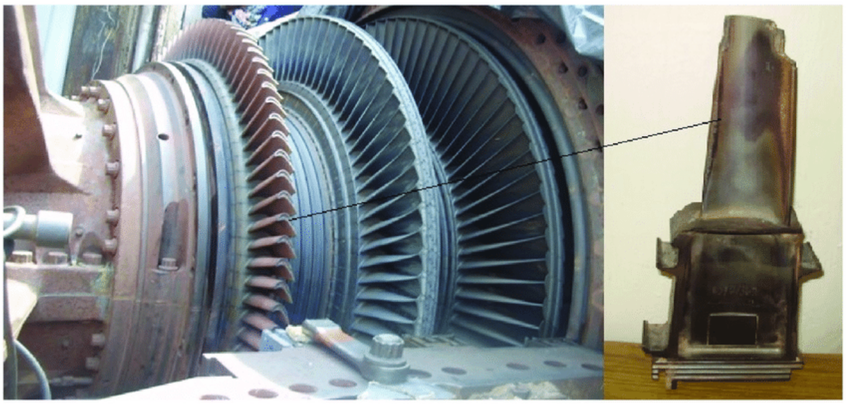


Figure I.16: First stage Gas Turbine Blade [34].

The temperature of the gases exiting the combustor, known as Turbine Inlet Temperature (TIT). TIT is a key factor influencing the thermal efficiency and performance of a gas turbine engine. Higher TIT generally leads to greater efficiency because it results in a larger temperature difference between high-temperature gases entering the turbine and lower-temperature ambient air or cooling air.

However, there are limits to the temperature To achieve a high Turbine Inlet Temperature (TIT) in gas turbines, several technologies and strategies are employed to enhance the performance and efficiency of the engine.

Figure II shows the increasing Turbine Inlet Temperature (TIT) trend in Rolls-Royce's alongside the maximum allowable temperature of nickel-base superalloys [32].

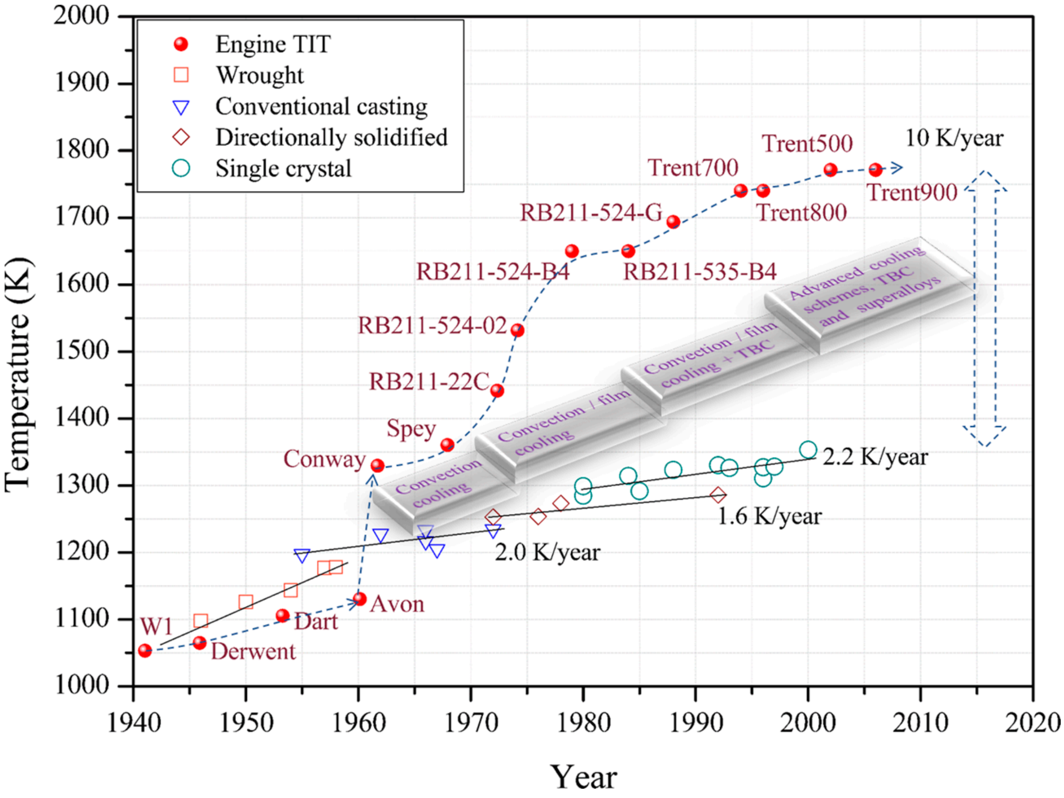


Figure I.17: Evolution of Turbine Inlet Temperature (TIT) in Rolls-Royce Civil Aero-Engines: Maximizing Superalloy Temperature Limits and Thermal Protection Techniques [32].

6 Need for Thermal Protection

During the early 1960s, technological advancements in turbine engineering resulted in instances where the Turbine Inlet Temperature (TIT) exceeded the prescribed limit for superalloys. This achievement was facilitated by the introduction of pioneering different cooling methods .
Subsequently, in the early 1970s, a significant breakthrough occurred with the introduction of combined film cooling and internal convection cooling methods. In the early 1980s, Thermal Barrier Coatings (TBC) were introduced on gas turbine vanes, capable of reducing temperatures by approximately 170 K [32].

In many high-performance turbine engines, blade cooling is a crucial aspect of design to manage the high operating temperatures, reaching the turbine inlet temperature (TIT) required for optimal performance would not be feasible without employing effective cooling techniques.The temperatures reached in the combustion process can far exceed the limits of the blade material without proper cooling [35].
Cooling techniques, such as (internal cooling passages, film cooling, transpiration cooling, and thermal barrier coatings), are essential for managing the high temperatures encountered in gas turbine engines.

6.1 Film cooling

The film cooling process typically involves the use of small holes or slots strategically positioned on the surface of the components. These holes allow the passage of cooler air from within the engine or from an external source, which forms a protective a thin film over the hot surfaces. This layer of cooler air acts as a barrier, reducing the temperature of the metal and protecting it from the direct impact of the hot gases. the cool air is often extracted from various stages of the compressor [36].
Figure(I.19) represente Film Cooling Technique on Blade Surfaces

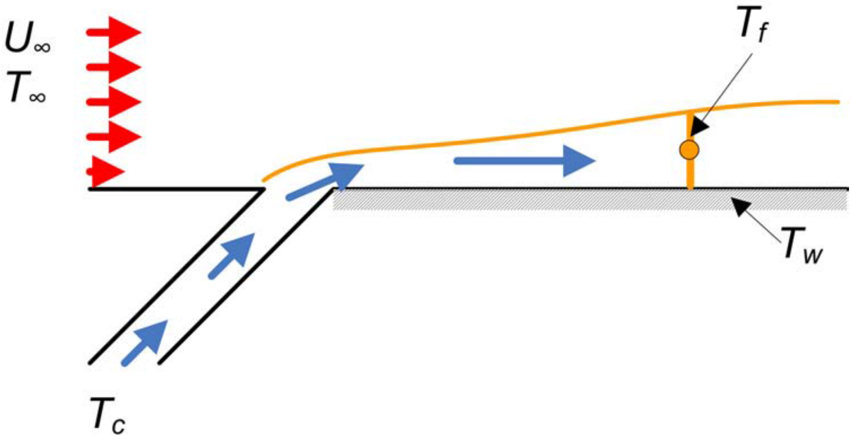


Figure I.18: Two-Layer Model for Film Cooling [35].

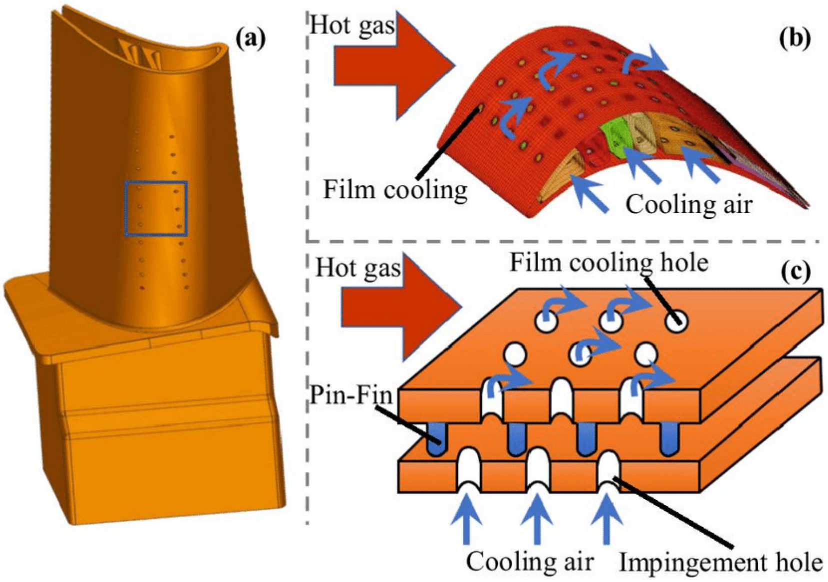


Figure I.19: Film Cooling Technique on Blade Surfaces[36].

Newton's Law of Cooling applied to a unit area of the surface. It represents the heat flux (q") between a fluid and a solid surface.

The heat flux equation is given by:

$$q'' = h(T_f - T_w) \tag{I.4}$$

where:

- (q”) is the heat flux per unit area (heat transfer rate per unit area),
- (h) is the heat transfer coefficient (in watts per square meter per kelvin),
- (T_w) is the local wall temperature (usually in Kelvin or Celsius),
- (T_c)is the coolant temperature
- (T_c)the driving temperature (film temperature),

While there is another effective method utilizing a porous material through which cold air can permeate and form a cooling film on the outer surface, is indeed known as transpiration cooling.

Transpiration cooling is considered one of the most effective methods for film cooling in certain applications, particularly in high-temperature environments such as those encountered in gas turbine engines.

the porous material allows the passage of a coolant fluid (often air) from within the structure to the external surface. This fluid then forms a cooling film as it interacts with the hot external environment. The porous material acts as a barrier, providing thermal protection to the underlying structure while facilitating efficient cooling [38].

6.2 Internal cooling

Several techniques are utilized to effectively cool turbine blades internally, ensuring their durability and performance. These techniques often involve the circulation of cooler air within the blade structure to extract heat and maintain the material within its operating limits. Internal cooling techniques for gas turbine blades indeed encompass various methods, including jet impingement, rib turbulated cooling, and pin-fin cooling [39].

Jet impingement involves directing coolant jets onto the internal surfaces of the blade, effectively enhancing heat transfer and cooling efficiency.

Rib turbulated cooling utilizes rib structures within the cooling passages to increase turbulence and promote heat transfer, thus improving cooling effectiveness. Pin-fin cooling, on the other hand, employs arrays of pin-like protrusions to enhance heat transfer by increasing surface area and inducing vortices within the coolant flow [40].

6.3 External cooling

External cooling of gas turbine blades involves the use of a cooling agent, typically air, passing through the blade surface to remove heat and maintain the material within acceptable temperature limits. This is crucial for preventing thermal stresses and avoiding failures due to creep and thermal fatigue. One well-established technique for external cooling is film cooling, which aims to achieve high overall cooling effectiveness while minimizing the impact on the thermodynamic cycle of the turbine.

Various methods are employed to enhance external cooling effectiveness and improve heat transfer:

- **Impingement Cooling:** Involves directing cooling air onto the surface of the blade through small holes or nozzles, which enhances heat transfer by breaking up the boundary layer and increasing convective cooling.
- **Rib Turbulated Cooling:** This method uses ribs or turbulators on the surface of the blade to enhance heat transfer by promoting turbulence in the cooling flow, increasing convective heat transfer.
- **Pin-Fin Cooling:** Incorporates pin-like protrusions on the blade surface to increase surface area and disrupt the boundary layer, improving convective cooling effectiveness.
- **Dimple Cooling:** Utilizes small depressions or dimples on the blade surface to enhance heat transfer by promoting flow mixing and turbulence, improving convective cooling.
- **Swirl Chambers:** Introduce swirl into the cooling air flow to enhance mixing and improve heat transfer, thereby enhancing cooling effectiveness.

- **Surface Roughness:** Controlled roughness on the blade surface can promote turbulence and enhance convective heat transfer, improving overall cooling efficiency.
- **Protrusions:** Employing small protrusions or fins on the blade surface can increase surface area and disrupt the boundary layer, improving convective cooling.

By combining these external cooling techniques with internal cooling methods such as internal passages with impingement cooling or serpentine channels for convective cooling, gas turbine blades can achieve efficient cooling while maintaining structural integrity and maximizing performance. This comprehensive approach to cooling is essential for ensuring the reliability and longevity of gas turbine blades in demanding operating conditions [40].
Figure I.7 Internal and external cooling for a gas turbine blade.

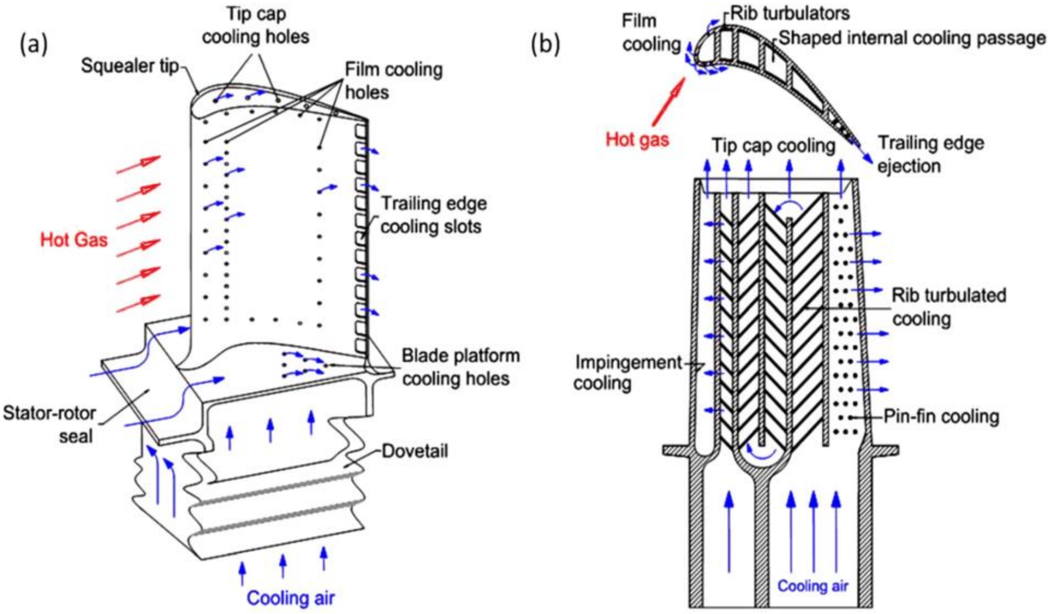


Figure I.20: Internal and external cooling for a gas turbine blade [41].

7 Thermal Barrier coating

In the realm of gas turbine technology, thermal barrier coatings (TBCs) have emerged as indispensable components for enhancing the performance and longevity of critical engine parts. (TBCs) are advanced materials applied to components exposed to high temperatures, such as gas turbine blades to enhance their performance and durability. These coatings, which form multilayer systems, it act as insulating layers for protecting underlying components from the extreme heat, oxidation, and corrosion experienced during engine operation [42].

The thickness of TBCs typically ranges from 100 to 500 micrometers μm and are made of a thermally insulating ceramic coating, such as yttria-stabilized zirconia (YSZ), which is applied over the conventional oxidation-resistant aluminide diffusion coating on the superalloy.
The primary purpose of thermal barrier coatings (TBCs) is to allow for higher operating temperatures in components without causing a corresponding increase in the metal temperature [43].

It can result in substantial reductions in the surface temperature of superalloys, typically in the range of 100° to 300°C or even higher, depending on the specific application and operating conditions [44].
the Figure (I.21) Represent heat transfer in turbine blades with a Thermal barrier coating [30].

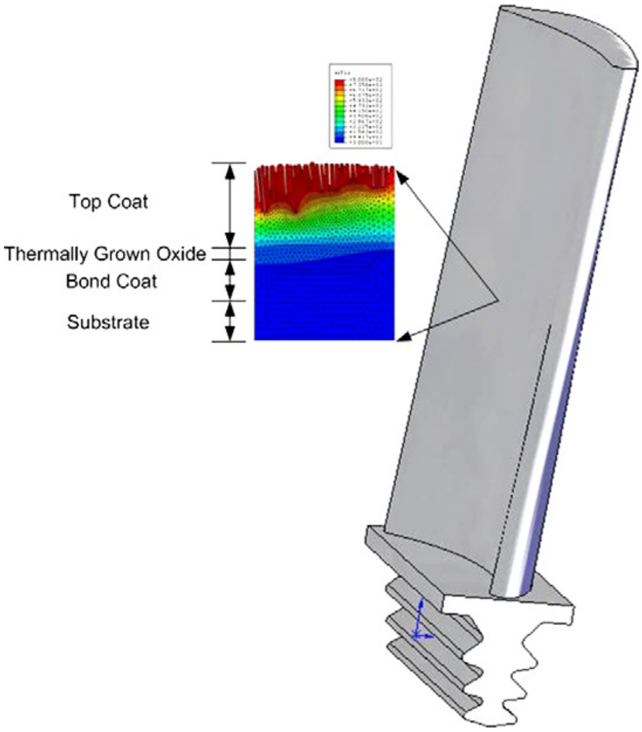


Figure I.21: Thermal barrier coating structure [45].

Thickness Profile of Layered Structure is shown in figure (I.22)

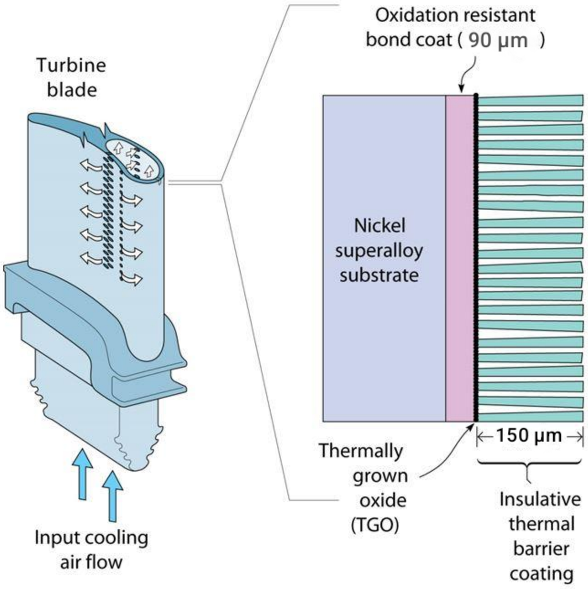


Figure I.22: Thickness Profile of Layered Structure [46].

The bond coat, often represented by MCrAlY alloy, typically consists of elements such as nickel (Ni), chromium (Cr), aluminum (Al), and yttrium (Y).
The M in MCrAlY can stand for various metals like cobalt (Co), iron (Fe), or a combination thereof, depending on the specific formulation. It is an oxidation-resistant metallic layer that is deposited directly on top of the metal substrate. It is typically 75-150 μm thickness [46].
The primary purpose of the bond coat is to protect the metal substrate from oxidation and corrosion, particularly from oxygen and corrosive elements that pass through the porous ceramic topcoat. The bond coat also reduces the thermal expansion coefficient mismatch between the ceramic topcoat and the metallic substrate and retards oxidation on the metallic substrate [47].
In the context of applying Thermal Barrier Coatings (TBC) to turbine blades, two methods commonly used, The first method is Atmospheric Plasma Spray (APS), which is a commonly used method for applying TBC. The second method is Electron Beam Physical Vapor Deposition (EB-PVD), which is a more expensive application option. EB-PVD is currently recommended for high-quality coatings due to its strain-tolerant coating that is produced. The thickness of TBC is limited by aerodynamic properties, weight, and abilities to ensure the top coat sticks to the bond coat without risk of spallation. Thicker TBC provides better insulation, but maximum thickness may be limited by these factors. TBC is only efficient if used together with other cooling techniques of a blade since it only insulates the blade and not actively cools it [48].

8 Problem Statement

Gas turbine blades are critical components in power generation and propulsion systems, operating under extreme conditions of temperature, pressure, and mechanical stress. To enhance their durability and performance, thermal barrier coatings (TBCs) and film cooling techniques are commonly employed. However, optimizing the design and implementation of these coatings and cooling strategies presents several challenges.

Existing research has focused on experimental investigations and theoretical analyses to understand the behavior of TBCs and cooling with a nano-fluid in gas turbine blades. While these studies have provided valuable insights, there remains a need for a comprehensive computational approach to systematically analyze and optimize the performance of TBCs and film cooling under various operating conditions.

The problem addressed in this thesis, titled "Analysis of the thermal distribution for a gas turbine blade with a Thermal barrier coating and a nano-fluid coolant." is the lack of a thorough understanding of how computational fluid dynamics (CFD) simulations, specifically using Ansys software, can be utilized to optimize TBCs and film cooling of gas turbine blades. This includes investigating the impact of manufacturing tolerances, geometric parameters, and operating conditions on the thermal performance, aerodynamic efficiency, and structural integrity of coated blades.

By addressing this problem, the thesis aims to bridge the gap between experimental research and computational modeling, providing a deeper understanding of the complex interactions between fluid flow, heat transfer, and coating materials. Ultimately, the goal is to develop more accurate and efficient computational tools for optimizing TBCs and film cooling strategies, leading to improved reliability, efficiency, and sustainability of gas turbine blades in power generation and propulsion applications.

8.1 Aims of the current study

- Analysis of temperature distribution throughout the gas turbine blade surface.
- Investigate the effectiveness of thermal barrier coatings (TBCs) and a nano-fluid cooling in enhancing the thermal protection of gas turbine blades.
- Conduct a comprehensive literature review to identify and evaluate the latest advancements in materials science and engineering related to thermal barrier coatings (TBCs), with a focus on identifying the most suitable materials for enhancing thermal protection and durability of gas turbine blades.

9 Conclusion

In this chapter of generalities, a comprehensive foundation for understanding the significance of thermal barrier coatings (TBCs) in enhancing the performance and durability of gas turbine blades. Through an exploration of the challenges faced in gas turbine operation, including high temperatures and harsh environmental conditions, the necessity for innovative solutions such as TBCs becomes evident. The chapter provides an overview of various methods utilized to improve gas turbine performance, emphasizing the critical role of blade materials and design. By delving into these key aspects, the stage is set for further investigation into the application, mechanics, and advancements of TBCs in subsequent chapters, ultimately contributing to the advancement of gas turbine technology.

Chapter II

Literature Review

1 Literature Review

This literature review chapter aims to provide a comprehensive overview of the existing research and advancements in gas turbine blade design configurations.

- **X.Q. Cao et al ,[49]**

  The study aims to summarize the fundamental properties of ceramics commonly used in TBC systems, providing insights into their suitability and performance. Through a meticulous synthesis of relevant literature, this review offers a comprehensive overview of ceramics suitable for TBC applications.

  By systematically categorizing and analyzing various ceramic options, it provides a nuanced understanding of their respective properties and compositions, thereby affording researchers and engineers a robust foundation upon which to base their material selection processes.

  There are various TBC materials, and their characteristics are summarized in the table.

Table II.1: The description of classes and their data

Materials	Advantages	Disadvantages
$La_2Zr_2O_7$	very high thermal stability low thermal conductivity low sintering not oxygen-transparent Commercial Registre of caterer	relatively low thermal expansion coefficient
7-8 YSZ	high thermal expansion coefficient low thermal conductivity high thermal shock resistance	sintering above 1473 K phase transformation (1443 K) corrosion oxygen-transparent
YSZ+CeO_2	high thermal expansion coefficient low thermal conductivity high corrosion-resistance less phase transformation between m and t than YSZ high thermal-shock resistance	increased sintering rate CeO_2 precipitation (> 1373 K) CeO_2-loss during spraying
Mullite	high corrosion-resistance low thermal conductivity good thermal-shock resistance below 1273 K not oxygen-transparent	crystallization (1023-1273 K) very low thermal expansion coefficient

.

another materials was showen in this study such as ,ZrO2,3YSZ,Al_2O_3,CeO2,$SrZrO_3$ ...

- **Aabid and Khan** , [50]

  In this study, Thermal Barrier Coatings (TBCs) have emerged as crucial protective measures for components in the hot sections of gas turbine engines, aimed at shielding them from the harsh effects of high temperatures. The primary objective of TBCs is to extend the service life of these components while reducing maintenance costs. The implementation of TBCs involves a multi-layered approach, typically comprising an initial coat, a bond coat, and a top coat, each serving distinct functions in enhancing the blade's durability and performance.

  A comprehensive approach was employed, incorporating both modeling and simulation techniques. Using CATIA software, a gas turbine blade was modeled to precise specifications. Subsequently, the heat transfer characteristics of the thermal barrier-coated blade were evaluated through numerical simulations conducted using ANSYS software, allowing for a detailed understanding of the thermal behavior and mechanical response of the coated blades under operating conditions. The analysis involved assessing thermal stresses and examining the effects of various TBCs on blade base alloys.

Figure (II.1) represente Thickness Profile of Layered Structure.

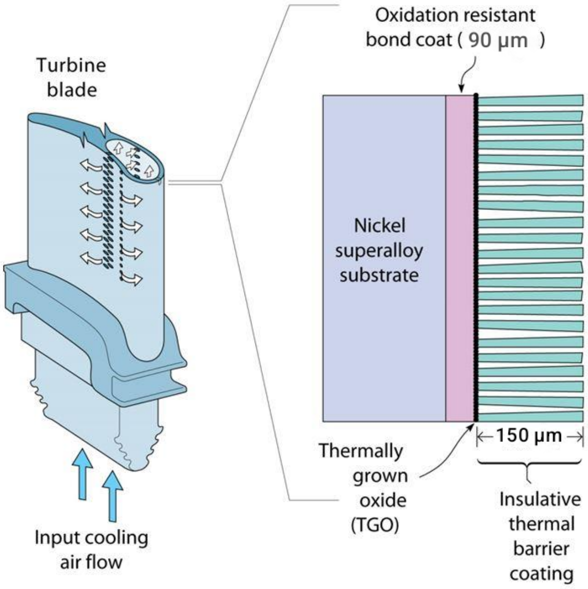


Figure II.1: Thickness Profile of Layered Structure

.

Various studies have investigated different combinations of TBC materials. Nanostructured ceramic-metallic composites have garnered significant attention as bond coats due to their unique combination of mechanical strength, thermal stability, and corrosion resistance. In all cases, Abbas and Khan used NiCoCrAIY as a bond coat.

In the cases, $La_2Zr_2O_7$ and 3YSZ were used as top coats, while Inconel 718, Chromium Steel, and Inconel 625 were utilized as substrate materials. The heat transfer coefficient and the temperature of the turbine inlet gas are 2028 W/m^2K and 1373 K, respectively.

Ultimately, the study suggests that the air plasma method, incorporating three layers of Inconel 718, NiCoCrAIY, and $La_2Zr_2O_7$, could be the most recommended for enhancing gas turbine blade performance. Through this simulation method, the study aims to contribute to the optimization of TBC design and implementation strategies, thereby enhancing the efficiency and reliability of gas turbine systems.

- **V,Sankar et al ,[51]**
  This literature review investigates the optimization of TBC thickness on gas turbine blades, focusing on the application of Partially Stabilized Zirconia (PSZ) as a barrier coating material. The study explores thermal and stress analysis conducted on Inconel 718 and Titanium-T6 blades, with emphasis on temperature distribution and heat flux along the blade surface.
  ANSYS simulations are utilized for analyzing the performance of TBCs with varying thicknesses of PSZ (ranging from 100 to 800 micrometers). Mathematical optimization techniques are employed to determine the optimum thickness of PSZ coating, considering factors such as temperature reduction, heat flux mitigation, and cost-effectiveness. Furthermore, comparative analyses between Inconel 718 and Titanium-T6 blades are presented, revealing the superior performance of Inconel 718 in terms of thermal stability and mechanical properties. As thickness increased, the temperature and heat flux decreased until reaching a certain value. Beyond this point, further increases in TBC thickness resulted in an increase in both heat flux and temperature.
  The findings underscore the effectiveness of PSZ as a TBC material and propose an optimal thickness of 550µm for achieving optimal performance of gas turbine blades.

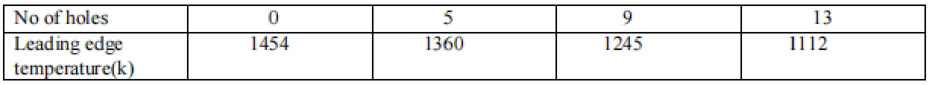
- **O, Sarikaya et al ,[52]** The study aims to discusse the use of the finite element method (FEM) to analyze temperature and stress fields in various plasma-sprayed coatings, particularly MgO-ZrO_2, Y_2O_3-ZrO_2 (YSZ), B_4C, and Al_2O_3. It investigates how these coatings affect thermal insulation properties and residual stresses, with NiCoCrAlY serving as a bond layer in the ceramic coatings. Among the coatings studied, MgO-ZrO_2 demonstrates the highest isolated heat capability. The paper also discusses temperature ratios among the ceramic coatings, with MgO-ZrO_2 exhibiting the highest insulation temperature value, indicating superior thermal insulation performance.

- **Sadowski et al ,[45]**

  Studied the study on the transient temperature transfer problem in bare and thermal barrier coated alloy Inconel 713 up to 1000°C presents valuable insights into enhancing the performance and longevity of turbine blades. By utilizing ANSYS Fluent (CFD) code to simulate the temperature field of combustion gas, the study offers a comprehensive analysis of the coupled system of fluid and structural elements. In the investigation, a TBC layer composed of ZrO_2 with 7 wt.% Y_2O_3, with a thickness of 0.5 mm, is applied.proves to be highly effective in reducing operational temperatures, yielding a significant decrease of approximately 18% in the analyzed numerical example. Furthermore, the integration of a system of five cooling channels within the turbine blade further contributes to temperature reduction, achieving a noteworthy decrease of about 7% in the numerical example.

  The combined approach of TBC application and cooling channel implementation demonstrates remarkable effectiveness, with the presented numerical results estimating a total reduction of approximately 25%. This indicates the potential for substantial improvements in engine operational temperatures, consequently extending the safe operational lifespan of the turbine blades.

- **KH.Brahmaiah et al , [53]**
  The current work investigated the heat transfer analysis in gas turbines using four different models, including blades without holes and blades with varying numbers of holes (5, 9, 13). The analysis was conducted using the Computational Fluid Dynamics (CFD) software FLUENT. Evaluation of the results, represented by graphs of the overall heat transfer rate and temperature distribution, revealed that the blade with 13 holes appeared to be the most optimal solution. Detailed analysis of the steady-state condition was performed using ANSYS software for thermal and structural analysis, employing different materials such as chromium steel and Inconel718. It was observed that the maximum temperature was concentrated at the leading edge of the blade. Comparison of thermal properties and induced stresses showed that Inconel718 outperformed chromium steel. The results are summarized in the following table :



No of holes	0	5	9	13
Leading edge temperature(k)	1454	1360	1245	1112

Figure II.2: Leading Edge Temperature Vs No of Holes.

- **Z.DU et al ,[54]**
  The study employed the conjugate heat transfer method to investigate the influence of thermal barrier coating (TBC) thickness ranging from 0 to 300 μm.

  The findings reveal that increasing TBC thickness results in a more uniform temperature distribution on the coated metal surface. Specifically, as the TBC thickness increases, the average temperature of the substrate decreases from 1158K to 1044K. This reduction in substrate temperature corresponds to a decrease in the high-temperature region, indicating improved thermal insulation provided by the thicker TBC.

Moreover, the study highlights that increasing TBC thickness leads to a more significant reduction in surface temperature and a contraction of the high-temperature region. Notably, the cooling effectiveness remains less sensitive to changes in surface roughness post-coating. However, increasing surface roughness alters heat flux distribution, with a decrease observed at the leading edge and an increase elsewhere.

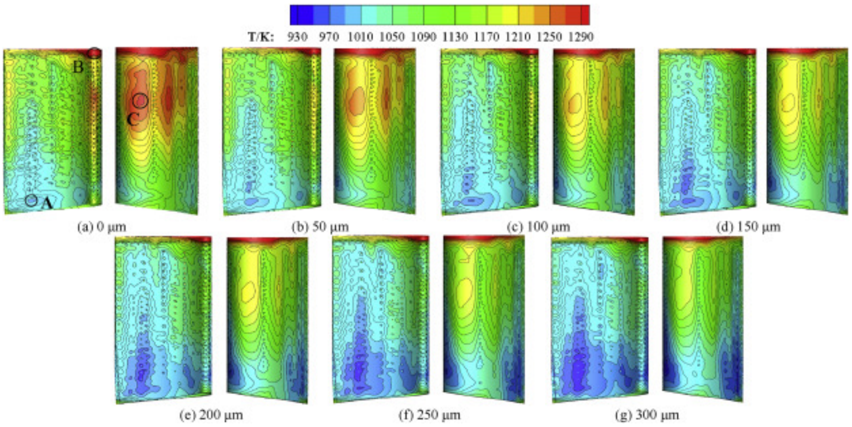


Figure II.3: Comparison of Surface Temperature Distributions on Blades with Varying Thicknesses

- **Z.Asl et al ,[55]** The study examines the impact of Thermal Barrier Coating (TBC) thickness on heat transfer between combustion gases and the blade body. Using a 3D model of both the blade body and TBC, the researchers found notable effects. Specifically, as the TBC thickness increases from 100 to 500 μm. , certain regions of the blade surface experience a significant 100 °C reduction in temperature. These results highlight the crucial role of TBC as an insulation layer for the blade core. Increasing the TBC thickness effectively reduces the temperature of the blade by up to 100 °C. This suggests that TBC serves as an effective means of thermal management, protecting the blade from high temperatures and potentially extending its lifespan.

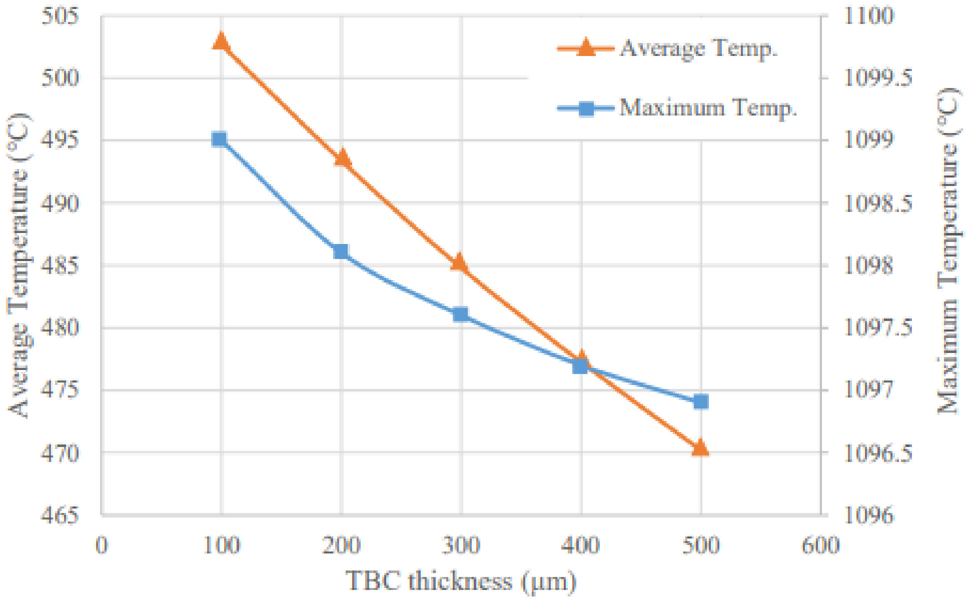


Figure II.4: Average and maximum temperature vs TBC thickness .

- **Nikhil Kumar H N et al ,[56]**
  The study focused on conducting both Static Structural and Computational Fluid Dynamics (CFD) analyses of gas turbine blade cooling, employing nano fluid as a coolant. Specifically, the investigation involved examining the cooling performance of blades with two different geometries: one featuring inline holes and the other with staggered holes. The analysis applied identical boundary conditions to both models to ensure comparability of results.

  In addition to the CFD analysis, the study introduced a novel bio-based method for the covalent functionalization of multi-walled carbon nanotubes (MWCNTs) using clove buds. This approach aimed to enhance the properties of the nano fluid coolant.

  Preliminary results indicate promising outcomes, suggesting that the cooling performance of the gas turbine blades is satisfactory. However, further analysis and validation may be necessary to comprehensively evaluate the effectiveness of the proposed cooling system and the impact of the bio-based functionalization method on the nano fluid coolant.

- **N. Asok Kumar et al ,[57]**

  Numerical simulations were employed to investigate the mechanisms of steady-state blade heat transfer, focusing on convection and radiation to the external surface of a super alloy blade, with and without a Thermal Barrier Coating (TBC). Results indicate that at a Turbine Entry Temperature (TET) of 1500 K, the radiation heat transfer rate from the gas to an uncoated blade constitutes 8.4% of the total heat transfer rate, which diminishes to 3.4% in the presence of a TBC.

  Moreover, it seems that in the presence of radiation and/or TBC, variations or uncertainties in the convection heat transfer coefficient don't significantly impact the metal temperatures. This suggests that the TBC and radiation play significant roles in altering heat transfer mechanisms, potentially mitigating the effects of variations in convection.

Overall, the study provides valuable insights into advanced thermal management techniques for turbine blades, highlighting the potential for significant enhancements in performance and durability. The findings underscore the importance of considering multifaceted approaches, such as TBC application and cooling channel systems, in addressing transient temperature challenges in high-temperature environments.
Finally, After several decades of extensive development in Thermal Barrier Coating (TBC) materials, it becomes evident that despite the myriad advancements, Yttria-Stabilized Zirconia (YSZ) continues to reign supreme. When assessing the multitude of properties required for successful TBC performance, it becomes apparent that YSZ stands out as a formidable contender that is challenging to replace. Its unique combination of thermal stability, mechanical robustness, and chemical resistance has solidified its position as a cornerstone material in the TBC landscape.
While, La2Zr2O7 has emerged as a potential competitor to Yttria-Stabilized Zirconia (YSZ) in the realm of Thermal Barrier Coating (TBC) materials. LZO offers several advantages that make it an attractive alternative to YSZ.

Indeed, numerous alternative materials have been explored and evaluated over the years, each with its own set of advantages and drawbacks. Yet, in comparison to YSZ, none have managed to achieve the same level of versatility and reliability across the spectrum of TBC requirements. While some materials may excel in specific areas, such as thermal conductivity or environmental durability, they often fall short in other crucial aspects, thereby hindering their overall suitability for widespread TBC applications.
The enduring prominence of YSZ underscores the formidable challenge inherent in finding a suitable replacement. Its well-established performance, coupled with a deep understanding of its properties and behaviors, positions it as the benchmark against which all other TBC

materials are measured. As such, while the quest for innovation and improvement in TBC materials continues unabated, YSZ remains firmly entrenched as the material of choice for many applications, a testament to its enduring legacy in the field of thermal barrier coatings.

2 Conclusion

In conclusion, this literature review chapter has comprehensively examined the various aspects pertinent to thermal barrier coatings (TBCs) applied to gas turbine blades, with a particular focus on the integration of nano-fluid cooling mechanisms. Through an extensive survey of existing research, this chapter has synthesized findings related to the materials utilized in TBC systems, including their composition, thermal properties, and deposition techniques. Furthermore, it has explored the significance of TBC thickness, elucidating its impact on thermal insulation effectiveness and mechanical stability. Additionally, this review has delved into the effects of parameters such as the number of cooling holes on temperature distribution across TBC-coated blades, shedding light on their role in enhancing heat dissipation and ensuring uniform thermal protection. By consolidating and analyzing a diverse range of studies, this chapter has provided valuable insights into the current state of knowledge regarding TBCs and their integration with nano-fluid cooling methods, laying the groundwork for the subsequent experimental and analytical investigations in this thesis.

Chapter III

Simulation Method

1 Introduction

This chapter is devoted to study the Numerical methods. This latter serve as indispensable tools in investigating heat transfer phenomena within TBCs.

Among these methods, the finite element method (FEM) stands out as a widely utilized approach due to its versatility and accuracy in solving complex heat conduction problems. By discretizing the domain into finite elements and applying appropriate boundary conditions, the FEM enables the numerical approximation of temperature distributions within TBC systems under various operating conditions.

2 Cfd

CFD stands for Computational Fluid Dynamics. It's a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems involving fluid flows.

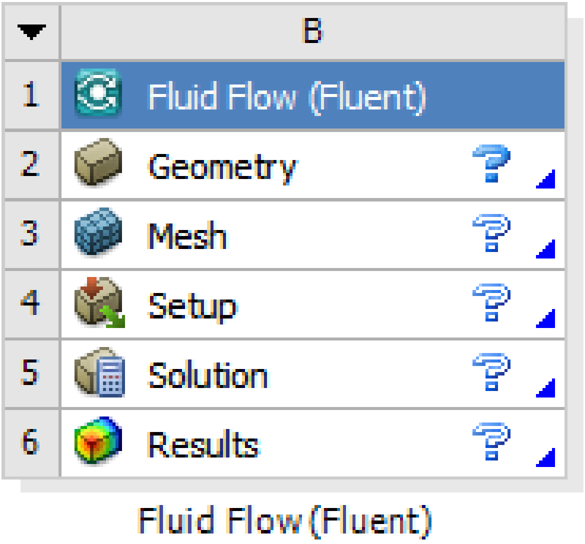
CFD is particularly useful when studying complex fluid flow phenomena, such as turbulence, heat transfer, and chemical reactions, where analytical solutions are often impractical or impossible to obtain.

2.1 ANSYS Fluent

ANSYS Fluent is a sophisticated computational fluid dynamics (CFD) software solution developed by ANSYS Inc. It offers engineers and researchers a robust platform for simulating and analyzing fluid flow and heat transfer in various engineering applications. With Fluent, users can model and simulate complex fluid flow phenomena with high accuracy and efficiency.

The graphical interface of ANSYS Fluent provides users with a user-friendly environment to set up, solve, and analyze computational fluid dynamics (CFD) simulations. It offers a variety of features and tools to facilitate the simulation process and visualize the results.

the figure (III.1) show The main window of the ANSYS Workbench software.



B
1 Fluid Flow (Fluent)
2 Geometry
3 Mesh
4 Setup
5 Solution
6 Results
Fluid Flow (Fluent)

Figure III.1: The main window of the ANSYS Workbench software.

2.2 The Steps

- Geometry:CAD model imported or created, ensuring well-defined boundaries and geometry quality for simulation.
- Mesh: Mesh generated with specified parameters, ensuring accuracy and quality suitable for numerical simulation.
- Configuration: Define boundary conditions, select solver settings, and set solution controls for accurate simulation.
- Solution: Run simulation, monitor convergence, evaluate solution quality for accurate numerical results
- Results: Post-process data, visualize results, analyze and quantify system performance for insights.

3 Governing Equations

The equations governing heat transfer and fluid flow in Computational Fluid Dynamics (CFD) models are rooted in physical conservation laws. The specific equations used depend on factors such as heat transfer conditions, flow characteristics, and parameters under investigation.

- Mass Conservation,
- Momentum Conservation,
- Energy Conservation.

These principles form the basis for mathematical formulations describing fluid flow and heat transfer phenomena in CFD simulations. By adhering to these principles and selecting appropriate equations tailored to the system's conditions, CFD models can accurately predict the behavior of fluids and heat within the studied domain.

1. Mass Conservation(continuity equation)

   Mass conservation, also known as the continuity equation, asserts that the mass of fluid entering a control volume must equal the mass leaving the volume, accounting for any accumulation or depletion within.

   $$\frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z} + \frac{\partial \rho}{\partial t} = 0 \tag{III.1}$$

   Where:

   - ρ is the density of the fluid (nano-fluid coolant),
   - $\mathbf{v} = (v_x, v_y, v_z)$ is the velocity vector field representing the fluid flow, with components along the x, y, and z axes respectively,
   - $\frac{\partial}{\partial x}$, $\frac{\partial}{\partial y}$, and $\frac{\partial}{\partial z}$ denote partial derivatives with respect to x, y, and z, respectively.

2. Momentum equations

   The momentum equations in fluid dynamics describe the conservation of momentum for fluid flow. the momentum equations can be expressed using the Naiver-Stokes equations. These equations consist of three components: the x component, the y component and the z component, representing momentum conservation in each direction. They are given as follows:

$$\frac{\partial(\rho v_x)}{\partial t} + \nabla \cdot (\rho v_x \mathbf{v}) = -\frac{\partial p}{\partial x} + \nabla \cdot (\mu \nabla v_x) + \rho g_x \tag{III.2}$$

$$\frac{\partial(\rho v_y)}{\partial t} + \nabla \cdot (\rho v_y \mathbf{v}) = -\frac{\partial p}{\partial y} + \nabla \cdot (\mu \nabla v_y) + \rho g_y \tag{III.3}$$

$$\frac{\partial(\rho v_z)}{\partial t} + \nabla \cdot (\rho v_z \mathbf{v}) = -\frac{\partial p}{\partial z} + \nabla \cdot (\mu \nabla v_z) + \rho g_z \tag{III.4}$$

   - ρ is the density of the fluid (nano-fluid coolant),
   - v_x, v_y, and v_z are the velocity components along the x, y, and z axes respectively,
   - p is the pressure,
   - μ is the dynamic viscosity,
   - g_x, g_y, and g_z are the components of the gravitational acceleration vector along the x, y, and z axes respectively.

3. Energy equation

   The energy equations in fluid dynamics describe the conservation of energy for fluid flow.

   The energy equations can be expressed using the energy conservation equation. This equation accounts for various energy transfer mechanisms, including conduction, convection, and radiation, and can be written in a general form as:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\rho E \mathbf{v}) = \nabla \cdot (k \nabla T) + p + \rho \mathbf{v} \cdot \mathbf{g} \tag{III.5}$$

- ρ is the density of the fluid (nano-fluid coolant),
- E is the total energy per unit mass,
- T is the temperature,
- k is the thermal conductivity (previously denoted as λ),
- p represents any heat sources or sinks (heat flux),
- $\mathbf{g}$ is the gravitational acceleration vector.

4. $k-\varepsilon$ Model

   The $k-\varepsilon$ turbulence model is one of the most widely used turbulence models in computational fluid dynamics (CFD) [58],[59],[60],[61]. It belongs to the family of two-equation turbulence models, where two additional transport equations are solved for the turbulent kinetic energy (k) and its dissipation rate (ε).

   The $k-\varepsilon$ turbulence model is based on the assumption of local isotropy of turbulence and provides a balance between accuracy and computational efficiency for a wide range of turbulent flows. In this model, the turbulent viscosity is computed from the turbulent kinetic energy and its dissipation rate, allowing for the prediction of turbulence effects on the flow field.

   Overall, the $k-\varepsilon$ turbulence model has been extensively validated and applied in various engineering applications, including aerospace, automotive, and environmental flows, making it a valuable tool for turbulence modeling in CFD simulations.

4 Method

In the initial phase of computational analysis, the process begins with the invocation of the ANSYS software platform. Following this, meticulous attention is devoted to crafting the geometric model using Space-Claim, where intricate details such as the inclusion of the thermal barrier coating thickness and the configuration of perforations are carefully integrated. Following the geometrical setup, the mesh generation process ensues, strategically partitioning the domain into discrete computational elements conducive to accurate simulation.

The simulation itself is executed through Fluent, a computational fluid dynamics solver renowned for its robustness and versatility. Before the start of the simulation run, comprehensive input parameters that encompass material properties, boundary conditions, and methodological specifications are meticulously defined. Upon completion of the simulation run, the focus shifts towards post-processing, wherein the generated data undergo rigorous analysis and visualization to glean insights into the heat transfer dynamics under scrutiny. This methodological framework ensures a systematic and comprehensive exploration of heat transfer phenomena within the confines of computational fluid dynamics, thereby facilitating deeper understanding and informed decision-making in relevant engineering contexts.

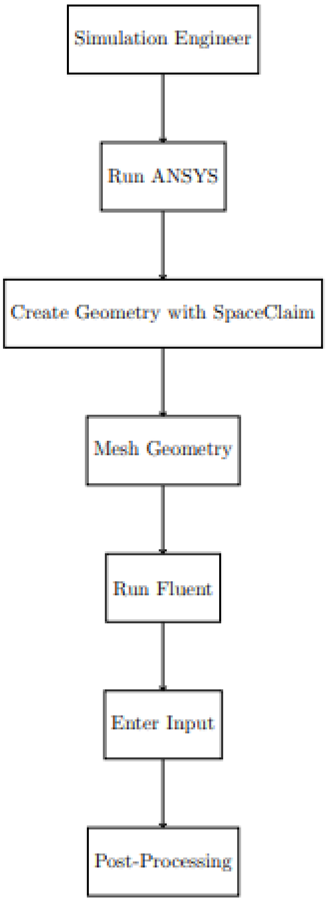


Figure III.2: Simulation process for the Heat transfer with cooling.

5 The processes of simulation

5.1 Creation of the geometry

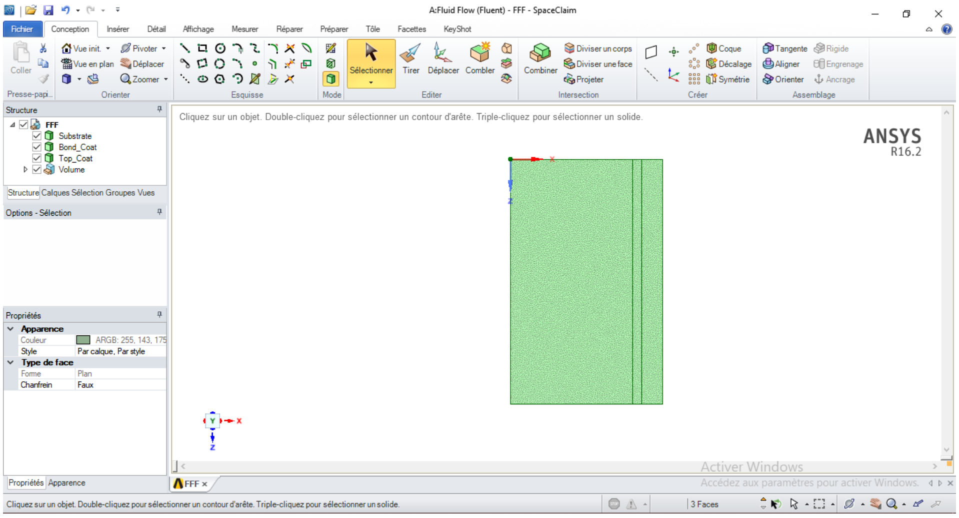
In the computational fluid dynamics (CFD) chapter of this thesis, the geometry of a gas turbine blade with a thermal barrier coating (TBC) system, incorporating cooling with a nano-fluid, is presented. The three-dimensional model, constructed using Space-Claim in ANSYS, comprises layers designed to withstand high-temperature environments typical in gas turbine operation. The substrate layer, composed of Inconel-718 super-alloy, forms the base of the coating system, with a thickness of 2mm. Above the substrate lies the bond coat, consisting of NiCoCrAlY, which serves as an intermediate layer to improve adhesion and resistance to oxidation, with a thickness of 0.15mm. The topmost layer, known as the top coat, is composed of Yttria-Stabilized Zirconia (YSZ) and provides thermal insulation, measuring 0.35mm in thickness. Nine cooling holes, each with a diameter of 0.5mm, are strategically positioned in the x-direction across the structure. These cooling holes facilitate the circulation of the nano-fluid coolant, which enters from the top coat side and flows towards the substrate, effectively dissipating heat from the TBC system. This comprehensive geometry serves as the foundation for subsequent CFD simulations aimed at evaluating the thermal performance and effectiveness of the proposed TBC-cooling system in gas turbine blade applications.

The creation of the geometry involved several steps to accurately represent the physical structure within the computational fluid dynamics (CFD) simulation environment. Using CAD software, such as SpaceClaim in ANSYS, , the intricate details of the layers of the TBC system were modeled to the geometry model. This involved creating distinct regions representing the substrate, bond coat, and top coat layers, each with their respective dimensions

The TBC system consists of:

- The first layer (Top coat):
  Length = 4mm height = 4mm Thickness=0.35µm.
- The seconde layer (Bond Coat):
  Length = 4mm height = 4mm Thickness=0.15µm.
- The third layer substrate.
  Length = 4mm height = 4mm thickness = 2mm.

The Domain of study is presented in the figures below.



Cliquez sur un objet. Double-cliquez pour sélectionner un contour d'arête. Triple-cliquez pour sélectionner un solide.

Figure III.3: Ansys geometry interface

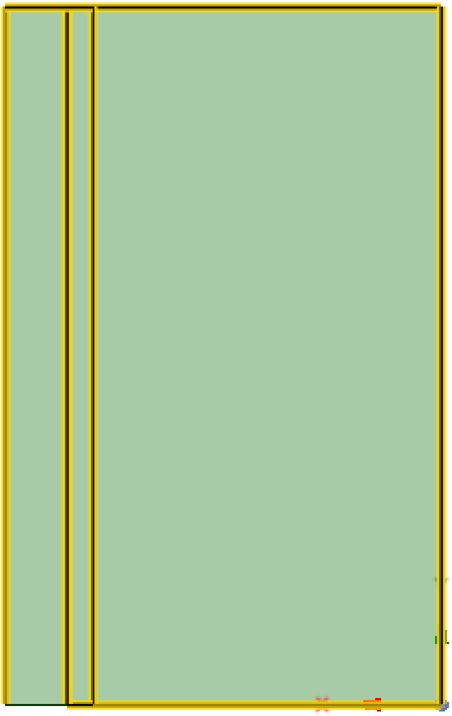


Figure III.4: Domain of study

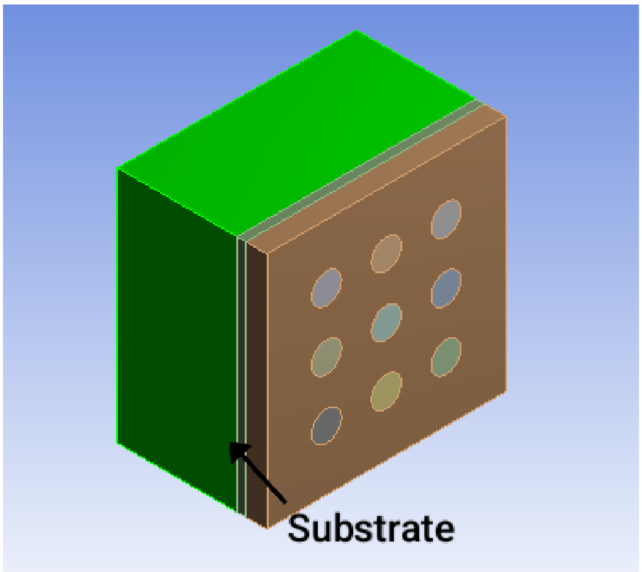


Figure III.5: Figure Show the Substrate.

5.2 Meshing:

The model was meshed ahead of the project start. The geometry model was divided into a finite number of elements. This involved specifying parameters such as element size, type, and distribution to ensure appropriate mesh resolution. Near-wall refinement techniques were applied to accurately capture the effects of the boundary layer, especially in regions of high flow gradients.

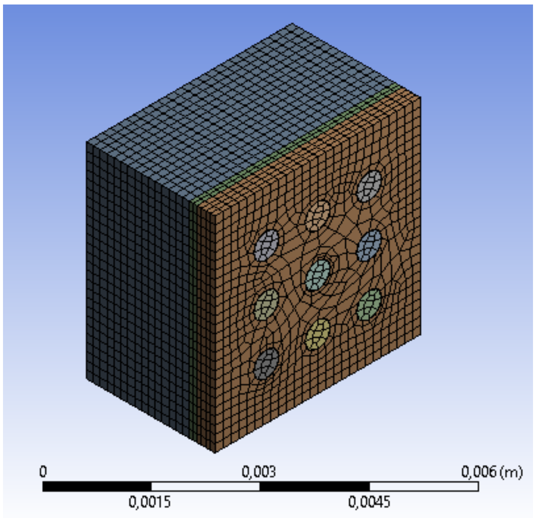


Figure III.8: Mesh of the Tbc system.

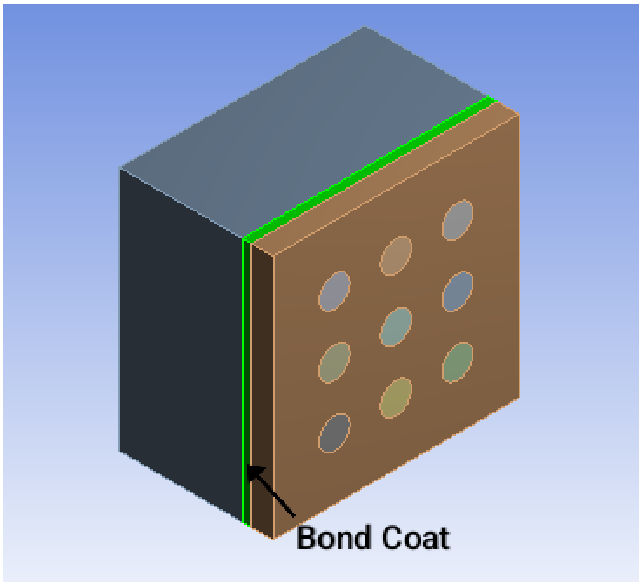


Figure III.6: Figure show the Bond Coat Layer.

Special attention was given to mesh quality to minimize distortion and improve numerical stability. Mesh quality metrics such as aspect ratio, skewness, and orthogonality were evaluated to ensure that the mesh was suitable for accurate numerical simulations.

In areas where geometric features or boundary conditions required finer resolution, mesh refinement was applied to increase the density of elements. This allowed for more precise representation of flow features and gradients, particularly around the TBC system and cooling holes.

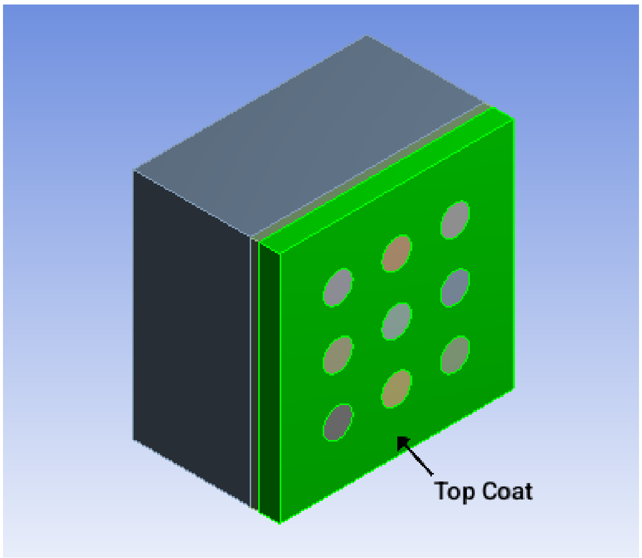


Figure III.7: Figure show the Top Coat Layer.

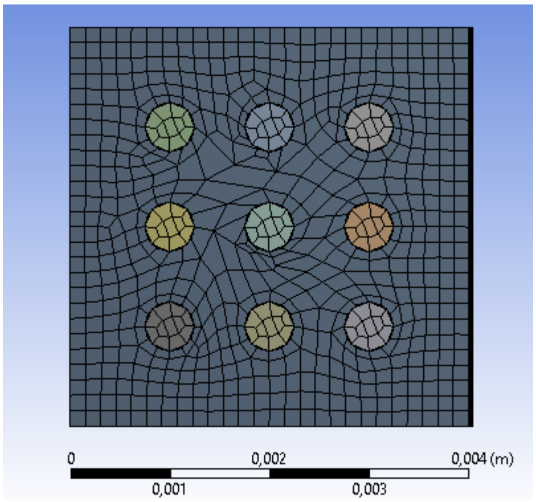
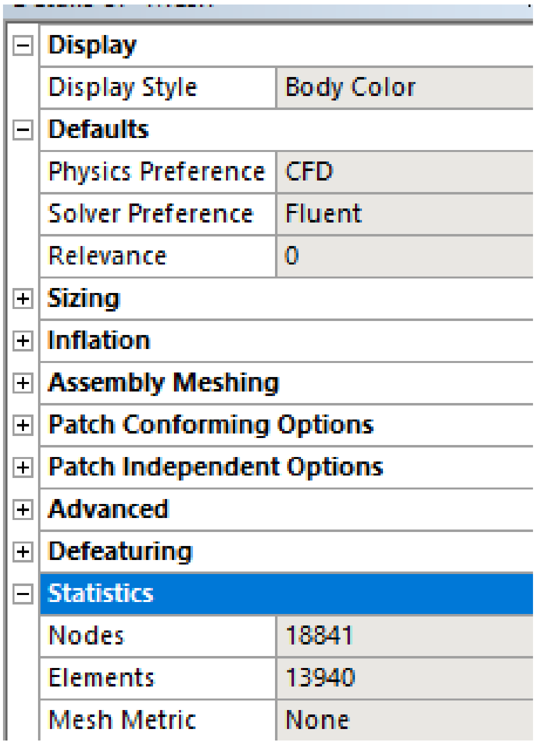


Figure III.9: Meshing of Geometric Features.

Overall, having 18841 nodes and 13940 elements.



⊟ **Display**	
Display Style	Body Color
⊟ **Defaults**	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	0
⊞ **Sizing**	
⊞ **Inflation**	
⊞ **Assembly Meshing**	
⊞ **Patch Conforming Options**	
⊞ **Patch Independent Options**	
⊞ **Advanced**	
⊞ **Defeaturing**	
⊟ **Statistics**	
Nodes	18841
Elements	13940
Mesh Metric	None

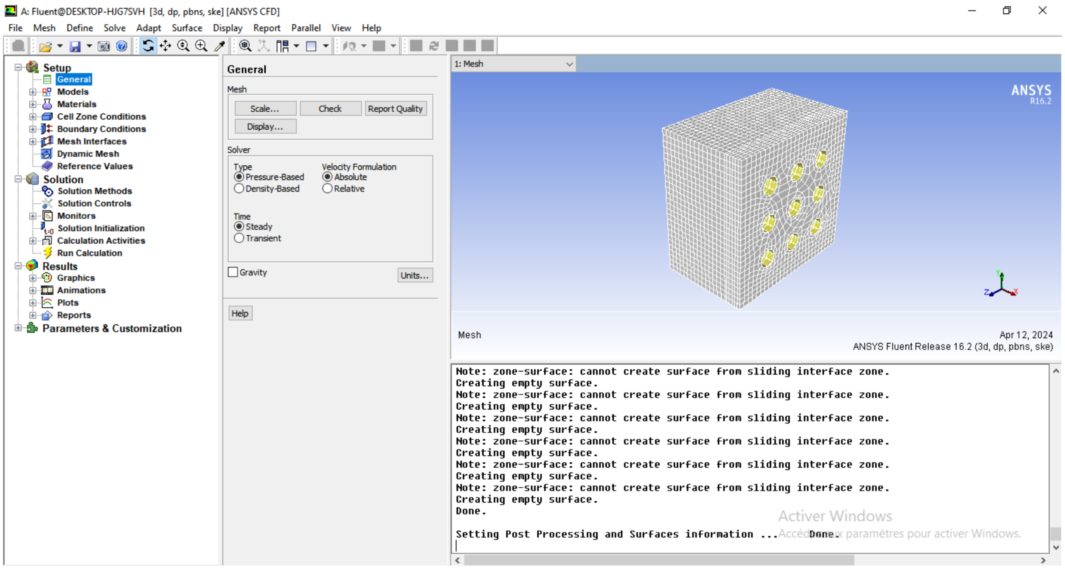
Figure III.10: Mesh data of models.

Once the meshing process was complete, the mesh was exported to the CFD solver, where it served as the computational domain for simulating fluid flow and heat transfer. The quality of the mesh played a significant role in the accuracy and reliability of the CFD results, making meshing a critical aspect of the simulation workflow.

5.3 Physics Setup and Boundary Conditions

5.3.1 Physics Setup

In the CFD solver, boundary conditions such as inlet velocity, temperature, materials, as well as any wall conditions are specified. In addition, the relevant physics models, such as turbulence modeling , are selected or customized based on the characteristics of the flow and thermal behavior.



Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
● Steady
○ Transient

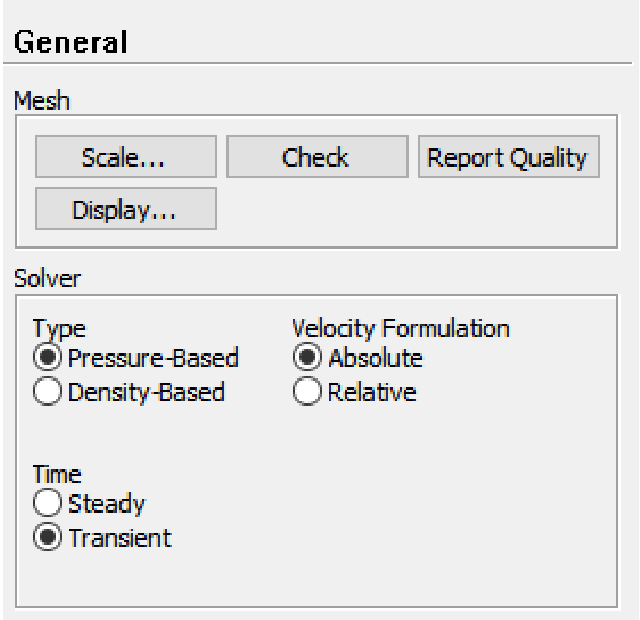
☐ Gravity

```
Note: zone-surface: cannot create surface from sliding interface zone.
Creating empty surface.
Note: zone-surface: cannot create surface from sliding interface zone.
Creating empty surface.
Note: zone-surface: cannot create surface from sliding interface zone.
Creating empty surface.
Note: zone-surface: cannot create surface from sliding interface zone.
Creating empty surface.
Note: zone-surface: cannot create surface from sliding interface zone.
Creating empty surface.
Note: zone-surface: cannot create surface from sliding interface zone.
Creating empty surface.
Done.

Setting Post Processing and Surfaces information ...Done.
```

Figure III.11: Ansys Fluent Interface.

We select the general configuration.



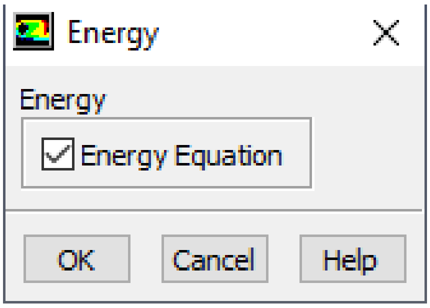
Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
○ Steady
● Transient

Figure III.12: General configuration.

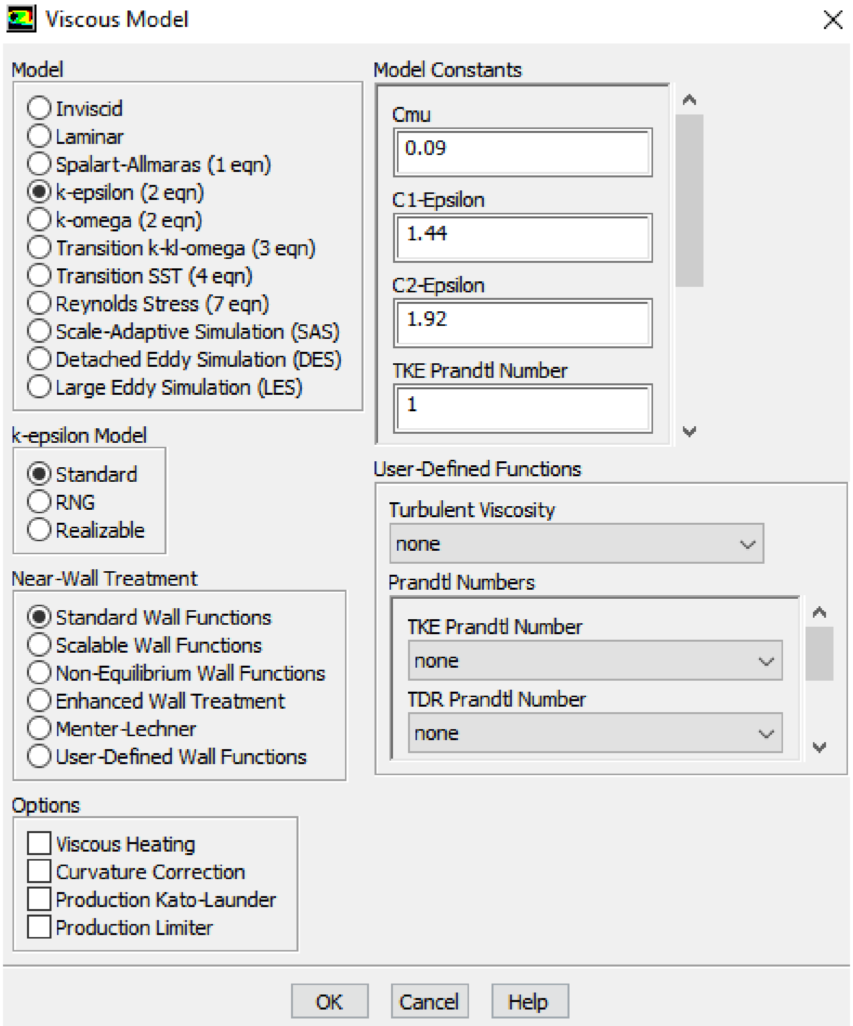
Enabling energy in ANSYS Fluent allows for the simulation of heat transfer and temperature distribution within the fluid domain. In the Fluent interface, in "Models" menu we enable the energy .



Energy
☑ Energy Equation

Figure III.13: Energy configuration.

After that we choose the $k - \varepsilon$ Model.



Viscous Model

Model
○ Inviscid
○ Laminar
○ Spalart-Allmaras (1 eqn)
● k-epsilon (2 eqn)
○ k-omega (2 eqn)
○ Transition k-kl-omega (3 eqn)
○ Transition SST (4 eqn)
○ Reynolds Stress (7 eqn)
○ Scale-Adaptive Simulation (SAS)
○ Detached Eddy Simulation (DES)
○ Large Eddy Simulation (LES)

k-epsilon Model
● Standard
○ RNG
○ Realizable

Near-Wall Treatment
● Standard Wall Functions
○ Scalable Wall Functions
○ Non-Equilibrium Wall Functions
○ Enhanced Wall Treatment
○ Menter-Lechner
○ User-Defined Wall Functions

Options
☐ Viscous Heating
☐ Curvature Correction
☐ Production Kato-Launder
☐ Production Limiter

Model Constants
Cmu: 0.09
C1-Epsilon: 1.44
C2-Epsilon: 1.92
TKE Prandtl Number: 1

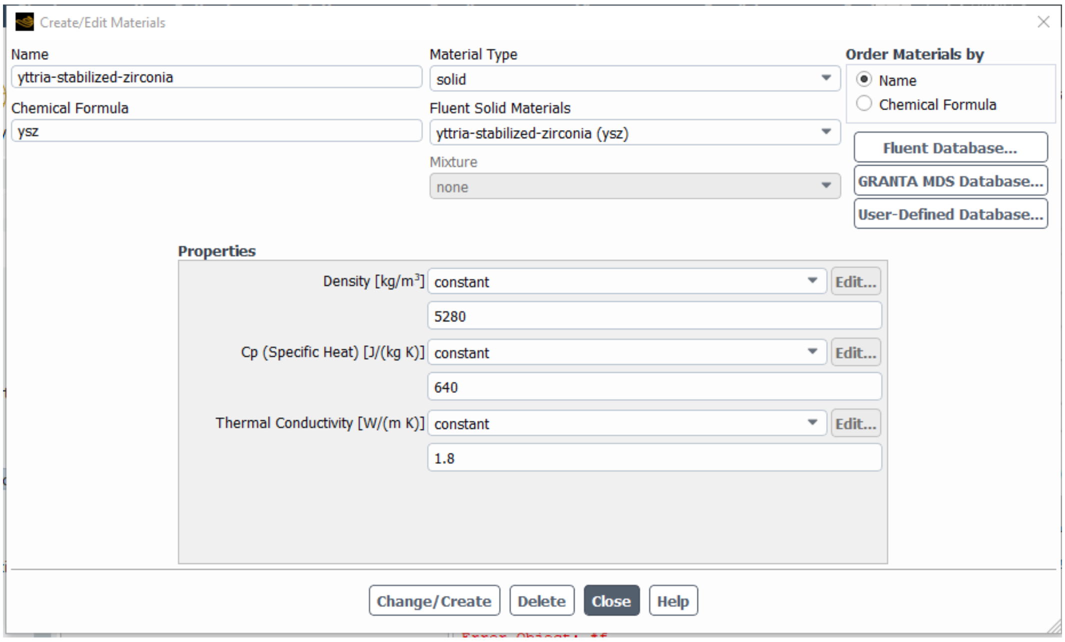
User-Defined Functions
Turbulent Viscosity: none
Prandtl Numbers
TKE Prandtl Number: none
TDR Prandtl Number: none

Figure III.14: $k - \varepsilon$ Model.

Then we Define Materials and applying materials to every Layer's. Material Properties Data.

Table III.1: Materials Thermal Properties[62],[63],[64].

	Density	specific heat	Thermal Conductivity	viscosity
Alumina Nanofluid	1112.2	4017.8	0.828	0.000672
Inconel-718	7884	690	26.9	/
NiCoCrAlY	5280	501	17	/
YSZ	5280	640	1.8	/


Name: yttria-stabilized-zirconia
Chemical Formula: ysz
Material Type: solid
Fluent Solid Materials: yttria-stabilized-zirconia (ysz)
Mixture: none
Order Materials by: ● Name ○ Chemical Formula

Properties
Density [kg/m^3]: constant
5280
Cp (Specific Heat) [J/(kg K)]: constant
640
Thermal Conductivity [W/(m K)]: constant
1.8

Figure III.15: Material configuration.

5.3.2 Boundary condition

These two figures show the inlet and outlet of the nano-fluid.

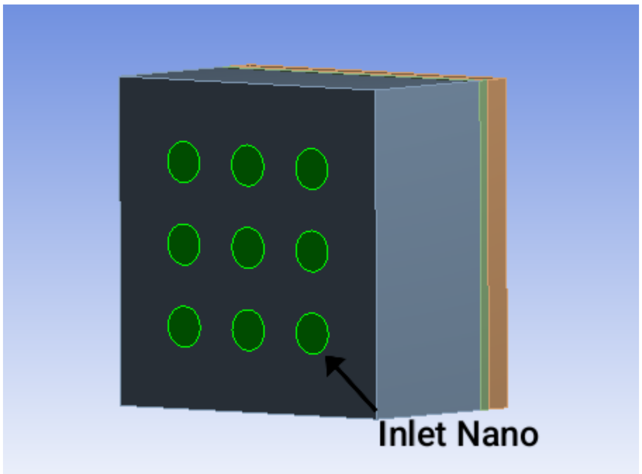


Figure III.16: The inlet volume of the nano-fluid.

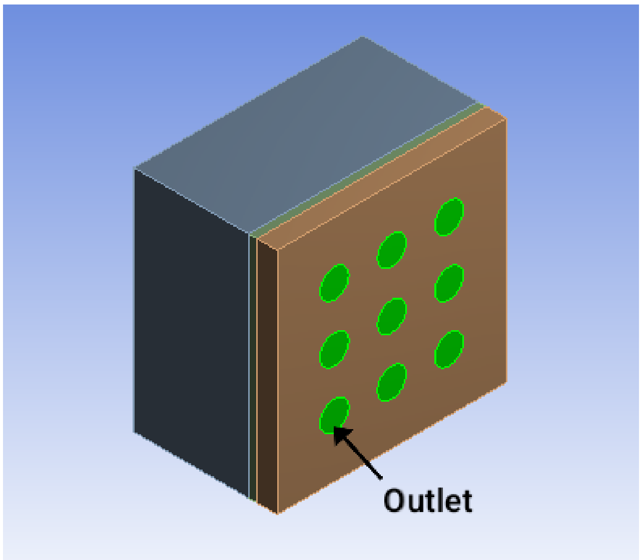
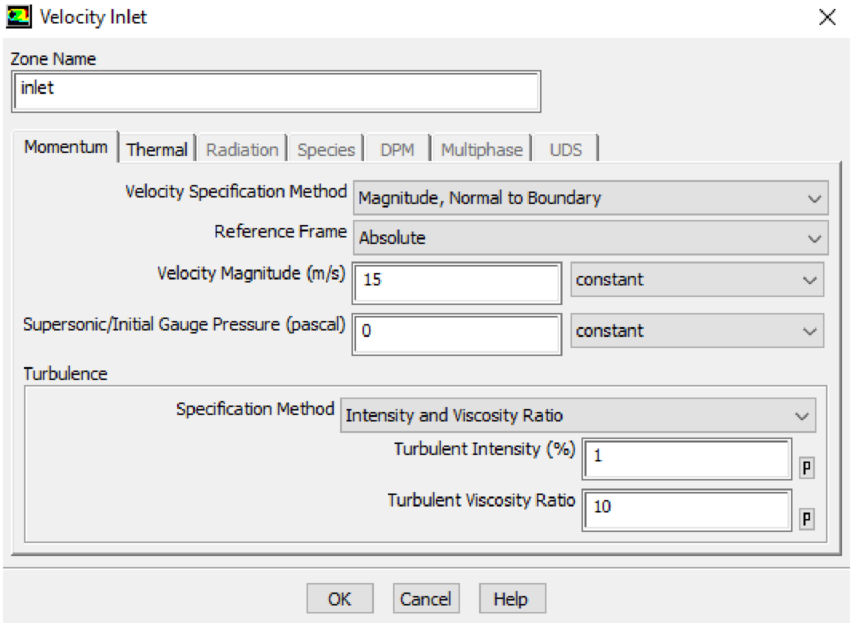


Figure III.17: The Outlet of the nano-fluid Domain.

<u>Nano-fluid properties</u>

The boundary conditions governing the fluid domain are set with an inlet temperature of 350 Kelvin and a corresponding velocity of 15 meters per second, representing the initial conditions for the nano-fluid introduction into the domain. These conditions aim to replicate real-world operating environments. Additionally, to simulate the inherent turbulence within the flow, a turbulent intensity of 1 percent is prescribed. This value reflects the expected fluctuations in velocity within the flow field.



Zone Name: inlet

Velocity Specification Method: Magnitude, Normal to Boundary

Reference Frame: Absolute

Velocity Magnitude (m/s): 15 constant

Supersonic/Initial Gauge Pressure (pascal): 0 constant

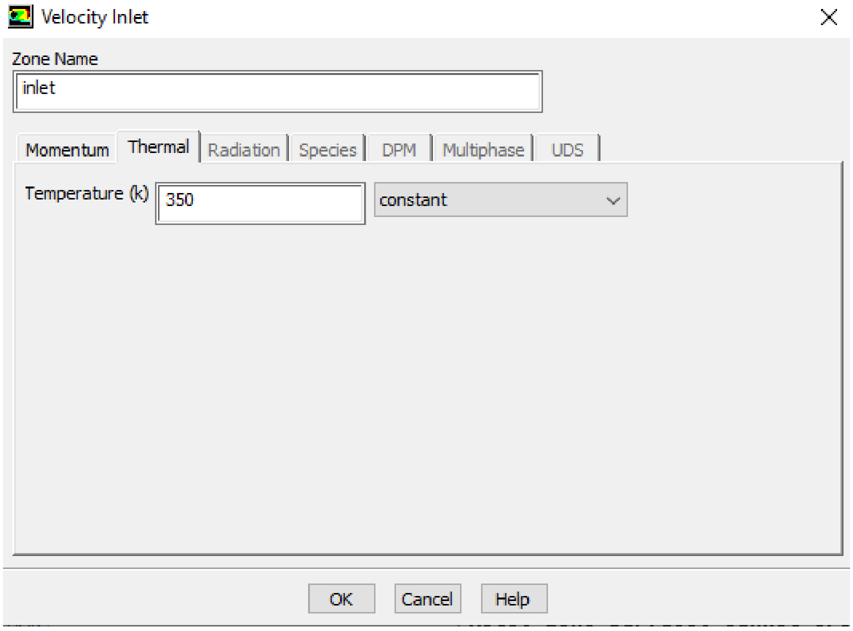
Turbulence

Specification Method: Intensity and Viscosity Ratio

Turbulent Intensity (%): 1

Turbulent Viscosity Ratio: 10

Figure III.18: The velocity and the turbulence parameters.



Zone Name: inlet

Temperature (k): 350 constant

Figure III.19: The temperature of the inlet nano.

In this study, a heat flux boundary condition is imposed on the face of the top coat layer, with a prescribed temperature of 1360 Kelvin.

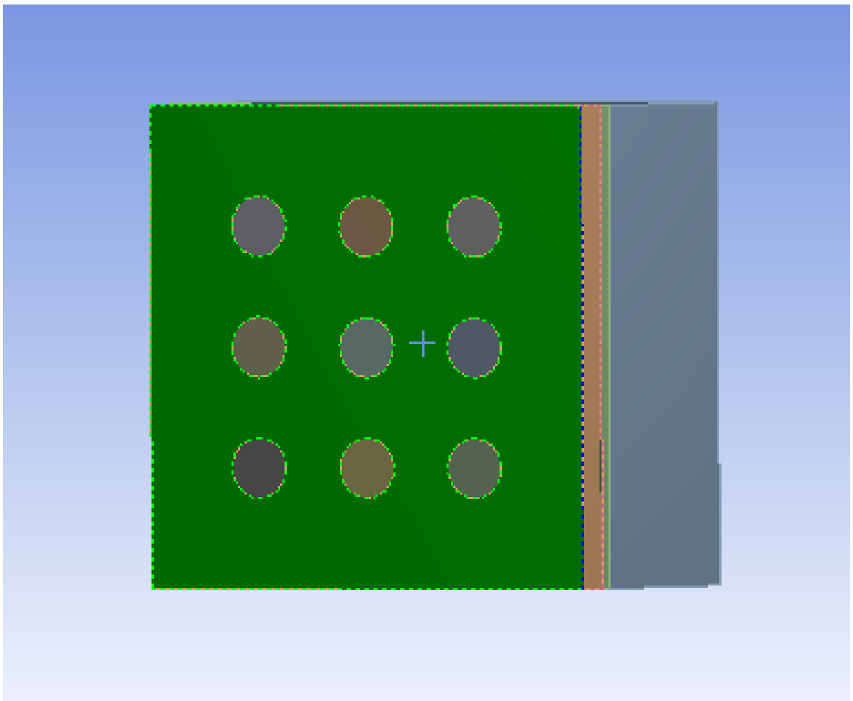
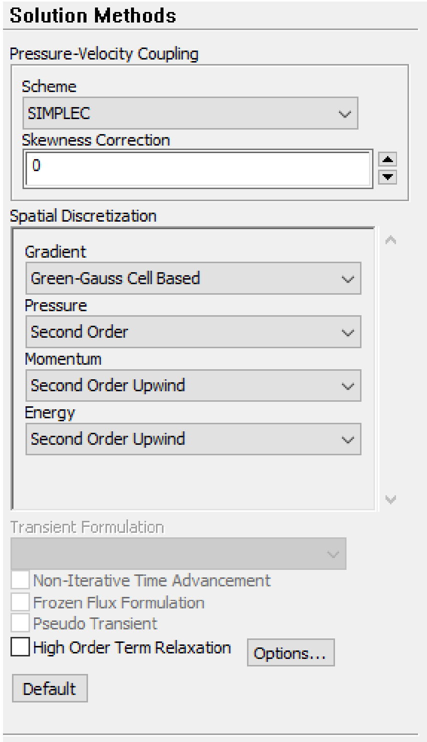


Figure III.20: Surface Region for Heat Flux Application

Solution methods:

Selecting the SIMPLEC (Semi-Implicit Method for Pressure-Linked Equations Consistent) algorithm as the solution method for the CFD simulation adds a significant computational advantage to the analysis of the thermal barrier coating system. With its robust and efficient approach, SIMPLEC offers a reliable framework for solving the governing equations of fluid flow and heat transfer, particularly suited for complex geometries and multi-physics phenomena. By adopting the SIMPLEC algorithm.

This choice reflects a strategic decision to balance computational efficiency with solution accuracy, thereby facilitating a thorough investigation of the thermal behavior of the TBC system within reasonable computational resources.



Solution Methods

Pressure-Velocity Coupling

Scheme: SIMPLEC

Skewness Correction: 0

Spatial Discretization

Gradient: Green-Gauss Cell Based

Pressure: Second Order

Momentum: Second Order Upwind

Energy: Second Order Upwind

Transient Formulation

☐ Non-Iterative Time Advancement

☐ Frozen Flux Formulation

☐ Pseudo Transient

☐ High Order Term Relaxation

Figure III.21: SIMPLEC Algorithm

Figure illustrates the sequential steps involved in the SIMPLEC algorithm, a computational method used in computational fluid dynamics (CFD) simulations .

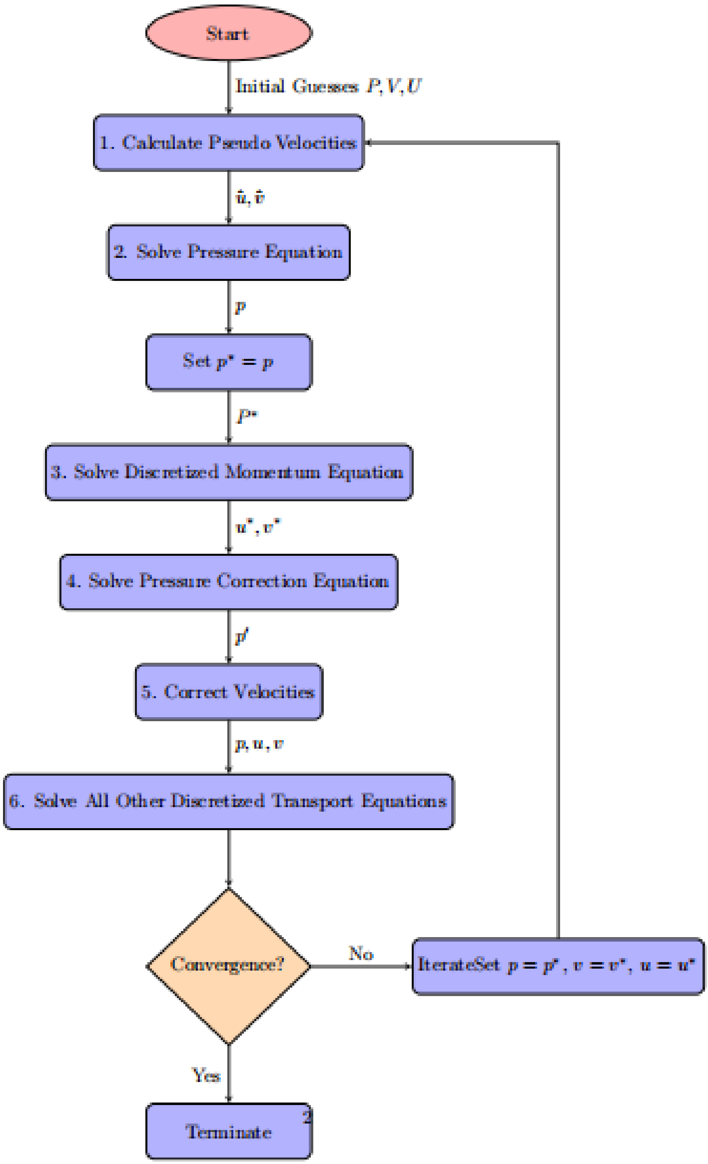
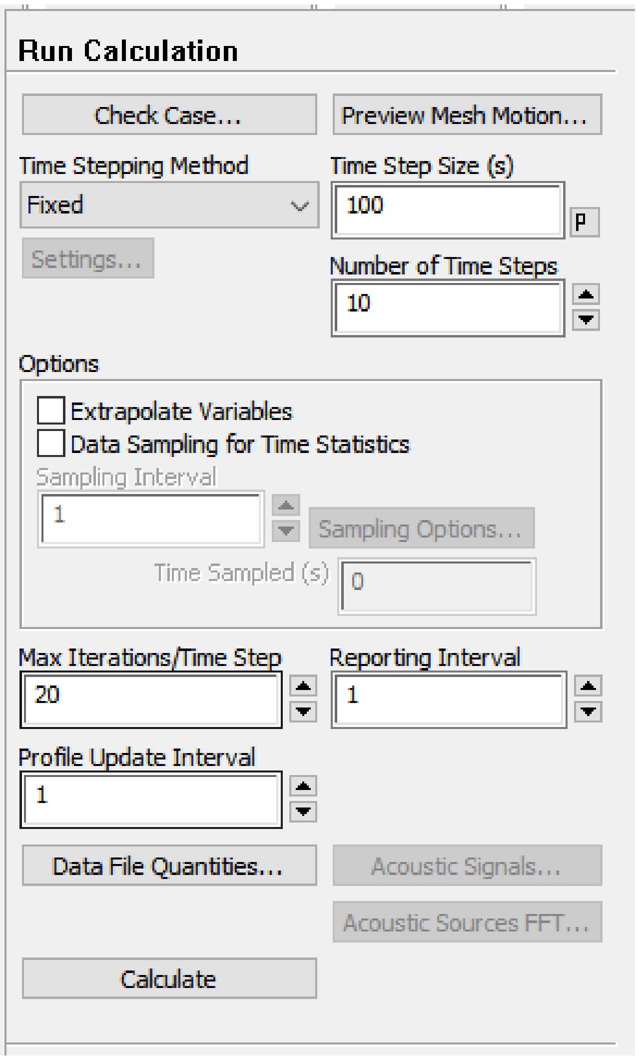


Figure III.22: Organigram of SIMPLEC Algorithm Steps for CFD Simulation after we configure the Transient time configuration :



Run Calculation

Time Stepping Method: Fixed

Time Step Size (s): 100

Number of Time Steps: 10

Options

☐ Extrapolate Variables

☐ Data Sampling for Time Statistics

Sampling Interval: 1

Time Sampled (s): 0

Max Iterations/Time Step: 20

Reporting Interval: 1

Profile Update Interval: 1

Figure III.23: Transient time configuration.

After all these steps we run the calculation.

Chapter IV

Results and discussion

1 Results

In this chapter, the results of the simulation regarding Thermal Barrier Coating (TBC) are presented.

Post-processing is the phase in the simulation in which we analyze the results obtained from the simulation.

We'll need to open the post-processing environment or module within this simulation software to visualize and analyze the results. This environment often provides tools and features for viewing various aspects of the simulation data, such as temperature contours, temperature profiles, heat flux distributions, and more.

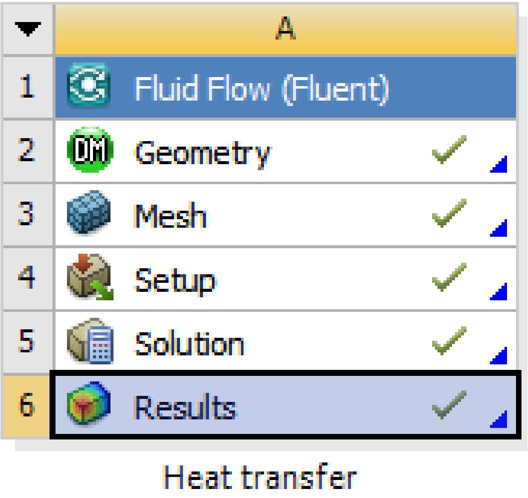


Figure IV.1: The window of the post-processing.

Figure (IV.2) likely presents the average temperature distribution within the thermal barrier coating (TBC) layers throughout the thickness.

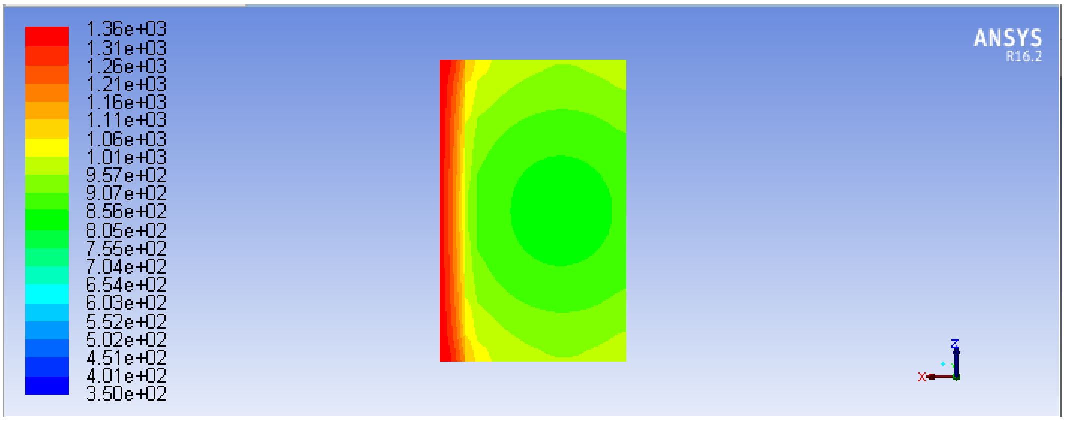


Figure IV.2: temperature distribution within the thermal barrier coating (TBC).

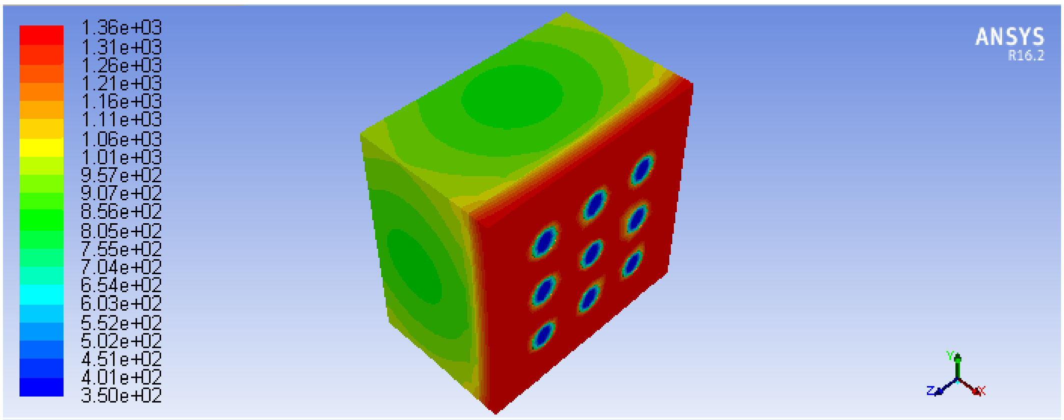


Figure IV.3: Temperature distribution of Layer’s.

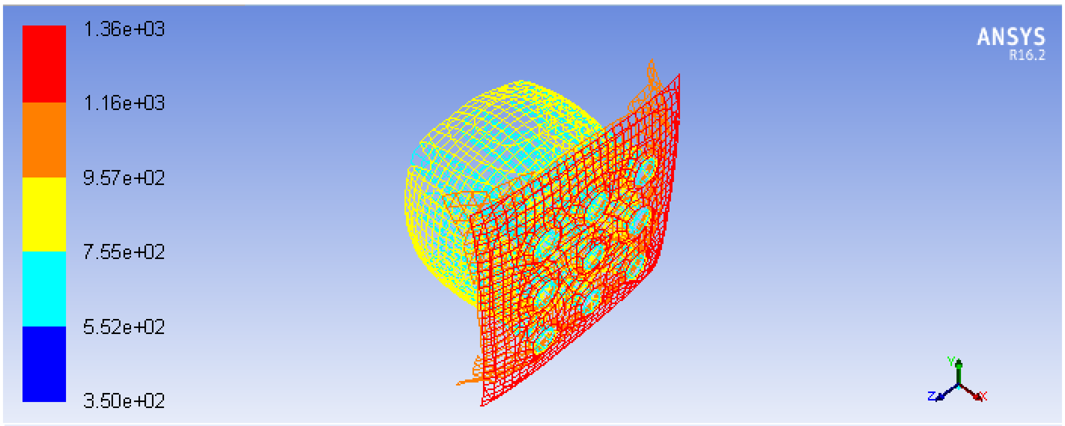


Figure IV.4: The temperature differential between the interior and the upper surface of the TBCs.

2 Discussion/Interpretation

The observed considerable temperature gradient through both the blade and the Thermal Barrier Coating (TBC) is a significant finding in thermal investigation. This gradient indicates variations in temperature along the length or thickness of the blade and the TBC layer, which can have important implications for their thermal performance and structural integrity.

The temperature reduction observed from the top coat to the substrate, with minimum temperatures occurring in the middle of the substrate layer (Inconel 718), involves several key factors that contribute to this phenomenon.

First, the thermal conductivity of the top coat and the bond layer play a significant role. The top coat, typically composed of Yttria-Stabilized Zirconia (YSZ), possesses good thermal properties, allowing it to efficiently insulate the underlying substrate from high temperatures. The bond layer also contributes to heat transfer management by facilitating the transfer of heat between the top coat and the substrate while maintaining structural integrity.

Secondly, the temperature of the nanofluid utilized in the system is relatively low, typically around 350 K. This low temperature of the nanofluid helps in cooling the system by absorbing heat from the substrate and promoting heat-exchange processes within the TBC structure.

Third, the properties of the nanofluid itself are crucial. Nanofluids are engineered suspensions of nanoparticles in a base fluid, often water or oil(water in this case).

These nanoparticles exhibit enhanced thermal conductivity compared to the base fluid alone. By introducing nanofluids into the system, the heat transfer capability is significantly improved, leading to more

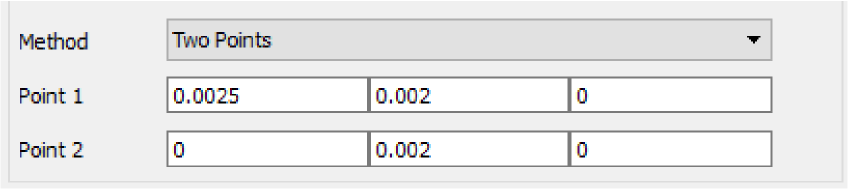
efficient cooling and temperature reduction within the TBC layers.
Lastly, the turbulence of the nanofluid flow enhances heat transfer efficiency. Turbulent flow within the TBC layers promotes better mixing of the nanofluid and increases the contact area between the fluid and the surfaces it comes into contact with. This turbulence facilitates faster heat exchange processes, leading to more effective cooling and temperature reduction.

Figure (IV.4) show The temperature differential between the interior and the upper surface of the substrate, with the interior reaching an average of 755 K while the upper surface exceeds that.
The observation that the outer surface of the substrate is significantly hotter than the interior is an expected behavior in many thermal systems and can be attributed to several factors.

- Firstly, the outer surface of the substrate is directly exposed to the high-temperature environment, such as the hot gases in a turbine engine. This direct exposure results in rapid heating of the outer surface, causing it to attain higher temperatures compared to the interior.
- Secondly, heat conduction plays a role in distributing the heat from the hot outer surface towards the cooler interior. However, due to the relatively low thermal conductivity of materials such as Inconel 718, which is commonly used as a substrate material in turbine applications, the heat transfer rate through the substrate is not instantaneous. This leads to a temperature gradient within the substrate, with the outer surface being hotter than the interior.
- Additionally, the presence of thermal insulation layers, such as the thermal barrier coating (TBC) and any surrounding cooling systems, further influences the temperature distribution within the substrate. These layers serve to mitigate heat transfer to the

substrate, particularly from the hot gases, but may also result in some insulation of heat generated within the substrate, leading to a temperature differential between the outer surface and the interior.

For creating a graph/chart, we Define the Line or the path along which we want to extract temperature data. This line should pass through the regions of interest where we want to analyze temperature distribution. The coordinates of the line typically related by two points(the starting and ending points of the line) . These points were be specified using Cartesian coordinates (x, y, z) in a 3D space(TBCs Layers).
Figure IV.1 show the coordinates of the line.



Method	Two Points		
Point 1	0.0025	0.002	0
Point 2	0	0.002	0

Figure IV.5: Definition of Line for Temperature Data Extraction: Starting and Ending Points.

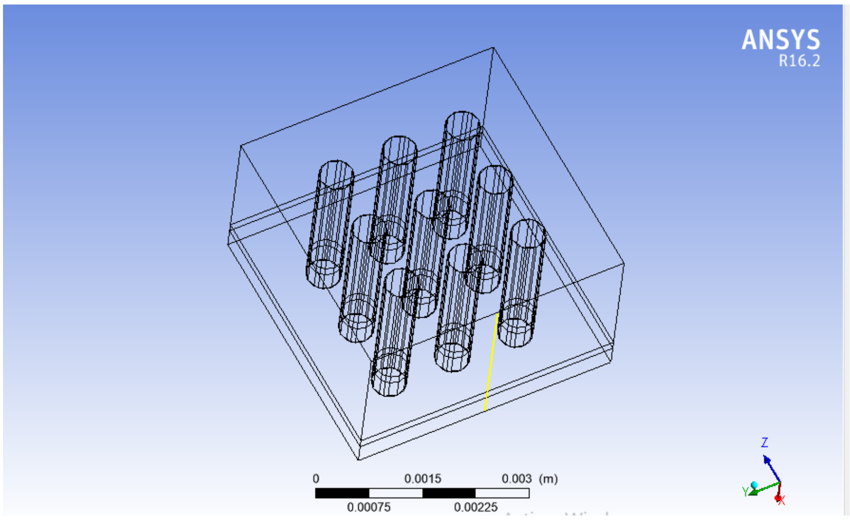


Figure IV.6: Line Across Thermal Barrier Coating Layers.

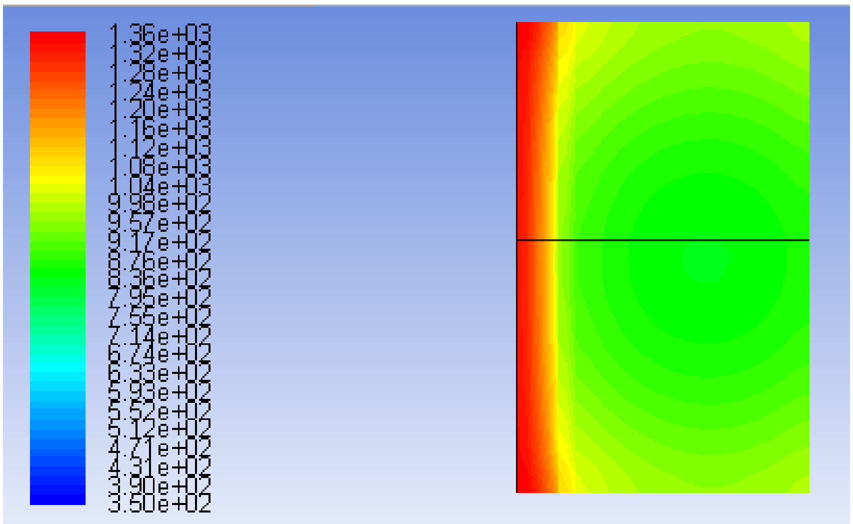


Figure IV.7: line Across Thermal Barrier Coating Layers 2.

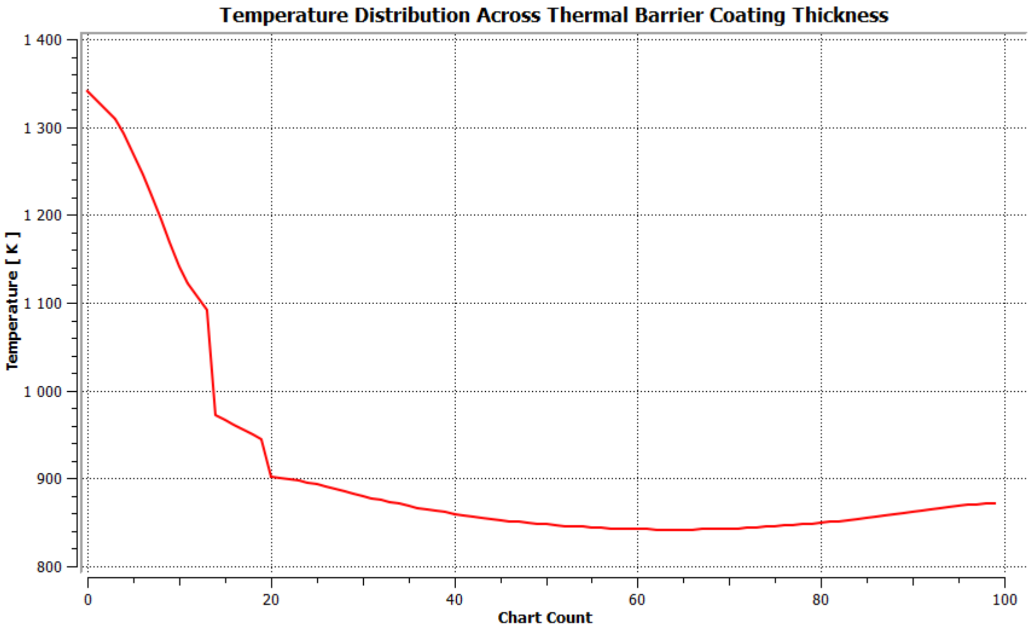


Figure IV.8: Temperature distribution across thermal barrier coating thickness.

Figure (IV.8) shows The graph shows the temperature distribution across the thickness of the thermal barrier coating (TBC) on a turbine blade.

2.1 Analysis of the temperature profile

Vertical Axis (Temperature [K]):

- The temperature ranges from 800 K to 1400 K.

Horizontal Axis (Thickness [mm]):

- (20 equal 0.5) Represents the thickness of the TBC layer, presumably in micrometers (mm),

Temperature Gradient:

- At the surface exposed to hot gases (left side of the graph), the temperature is highest, around 1360 K.
- Moving inward through the TBC, the temperature drops significantly.
- As we go deeper into the coating, the temperature continues to drop but at a slower rate, eventually stabilizing.

Thermal Gradient Analysis:

- The initial sharp decline (around 0 to 0.5 mm Thickness) reflects the effectiveness of the TBC's Bond and top-coat insulating with the velocity and the turbulence of the nano-fluid in against high temperatures.
- The gradual decline that follows (from 0.5 mm to 125 Thickness) which represents the transition through the bond-coat and into the substrate. This region also contributes to thermal resistance but to a lesser extent than the top-coat.
- After approximately 125 Thickness, the temperature stabilizes around 830-900 K, suggesting the region closer to the substrate where the nano-fluid cooling effect becomes more prominent.

Stabilization Region:

- The region where the temperature curve flattens out indicates the nano-fluid cooling influence inside the blade, maintaining a more constant temperature.

as illustrated in the graph, reveals the effectiveness of the TBC system in insulating the underlying superalloy substrate from high temperatures. At the surface exposed to hot gases, the temperature is approximately 1360 K, the temperature tends to be highest due to direct exposure to the heat source or high temperature environment. This surface experiences the maximum heat flux and is subjected to the full extent of thermal loading.

As a result, it reaches the highest temperatures within the system.
In contrast, moving inward, the temperature drops sharply within the top and the bond coat, indicating the significant thermal resistance provided by these two layers which are closer to the substrate, the temperature tends to decrease. This is because the substrate acts as a heat sink, absorbing and dissipating heat away from the TBC layers. Additionally, heat conduction through the TBC layers towards the substrate contributes to cooling the inner surfaces.
This steep decline is followed by a more gradual decrease through the substrate, continuing until around 50 micrometers where the temperature stabilizes between 850-900 K. This stabilization reflects the impact of the cooling by the nano-fluid, which maintains a more consistent and lower temperature closer to the substrate
Additionally, the substrate material itself has thermal mass and heat dissipation properties that help regulate its temperature.

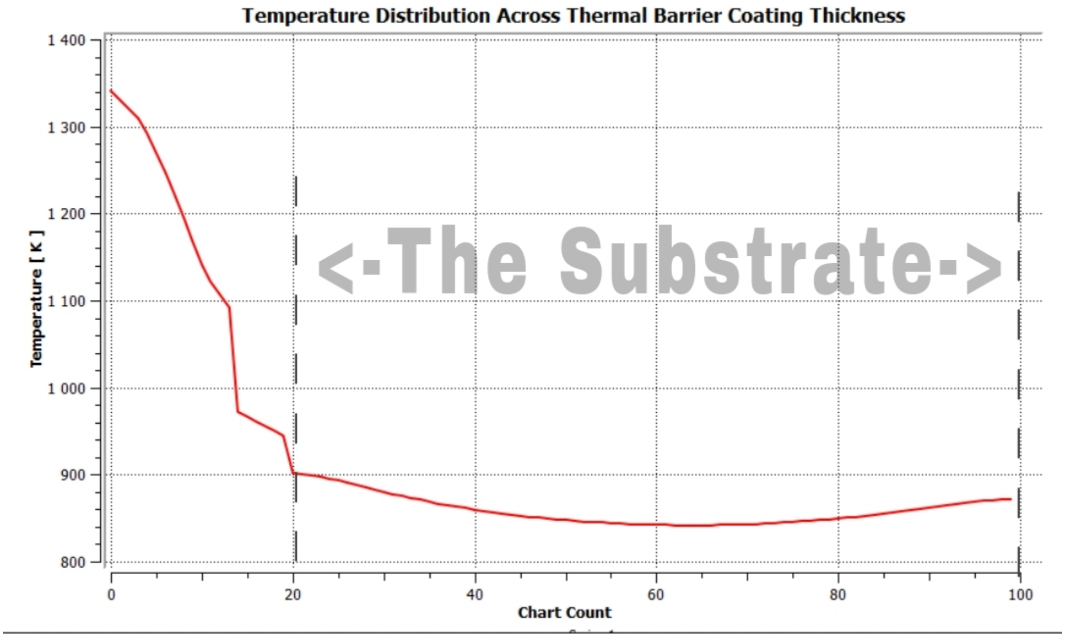


Figure IV.9: Temperature distribution across thermal barrier coating thickness.

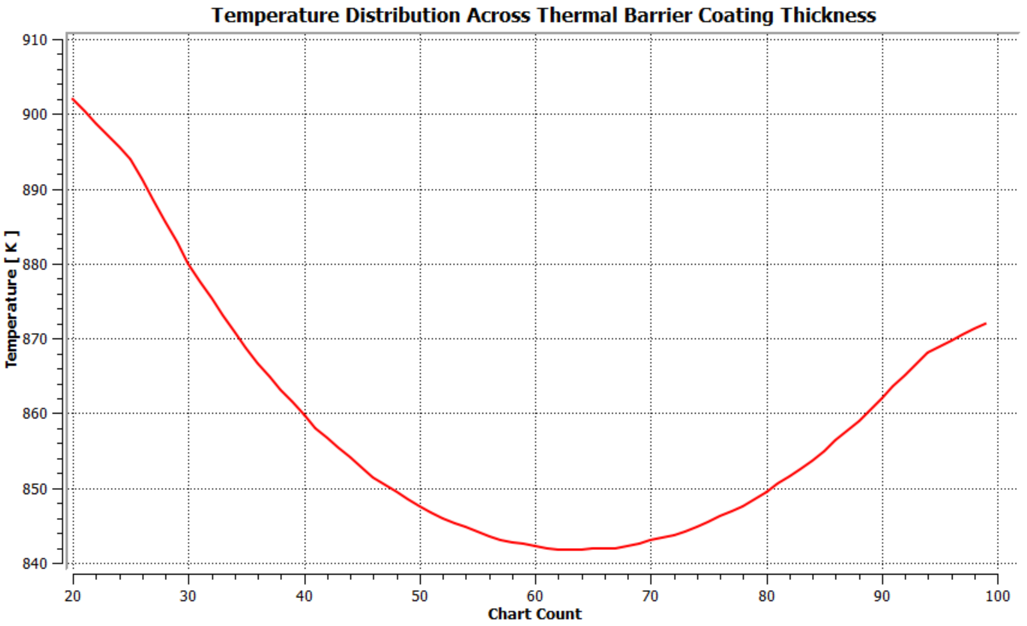


Figure IV.10: Temperature distribution across the substrate.

3 Comparison

O,Sarikaya et al ,[65]

The investigation into the heat transfer characteristics of ceramic coatings in thermal barrier applications focuses on how different types of coatings affect thermal insulation properties.

The study employs finite element codes to optimize various factors such as composition, layer structure, and thickness of the coatings.

- **Substrate Material:**

  Inconel 718 is used as the substrate material in all cases (nickel-chromium-based superalloy).

- **Bond Coat Material:**

  NiCoCrAlY is utilized as the bond coat in all cases.

- **Coating Composition and Structure:**

  Different compositions and structures of ceramic coatings are tested to determine their impact on thermal insulation.

- **Case Study:**

  A specific case, referred to as Case B, is highlighted where a combination of a bond coat (NiCoCrAlY) and a top ceramic coat is analyzed without the influence of a nano-fluid and turbulence.

The results of the study indicate that the temperature differences calculated between the coatings with a YSZ (yttria-stabilized zirconia) surface and the coating-substrate system averaged around 120°C. This significant temperature differential highlights the superior thermal insulation properties of the YSZ surface compared to other coating configurations.

4 Conclusion Remarks

The analysis of temperature evolution in a 3D plate, utilizing Fluent Ansys, offers valuable insights into the thermal behavior of the system. Focus was directed towards the temperature distribution over time, particularly emphasizing the interaction between the Thermal Barrier Coating (TBC) system and the nanofluid coolant.

Initially, the temperature on the upper surface of the TBC was registered at 1360 K, gradually decreasing to 840 K within the 1000 second interval. This decline highlights the combined influence of the TBC and the nanofluid in facilitating heat exchange and effectively managing thermal loads.

Of particular note is the substantial reduction in temperature by over 500 Kelvin from the top coat's upper surface to the substrate's upper surface. This underscores the remarkable thermal insulation capabilities conferred by both the TBC and the nanofluid coolant.

The synergistic effect of the TBC and the nanofluid is evident in their ability to impede heat transfer effectively, ensuring that the substrate remains at a lower temperature. This finding emphasizes the importance of integrating multiple thermal management techniques for optimal performance in high-temperature environments.

In summary, the results demonstrate the effectiveness of the TBC system and nanofluid coolant in mitigating thermal stresses and preserving the structural integrity of the substrate material. This underscores their potential in enhancing thermal management strategies for various applications, particularly in industries where elevated temperatures pose operational challenges.

5 Conclusion

In conclusion To optimize thermal barrier coatings (TBCs) for maximizing the thermal protection and durability of gas turbine blades under high-temperature operating conditions, several key strategies can be employed. These include:
Material Selection:
Choose TBC materials with high thermal stability, low thermal conductivity, and good adhesion to the substrate material. Common TBC materials include yttria-stabilized zirconia (YSZ) and rare-earth oxide-based ceramics. Conduct thorough research and experimentation to identify the most suitable material for the specific operating conditions of the gas turbine.
Optimized Coating Thickness:
Determine the optimal thickness of the TBC layer to achieve the desired balance between thermal insulation and mechanical integrity. Thicker coatings typically offer better thermal protection but may be prone to spallation and crack formation. Conduct simulations and experiments to determine the ideal thickness for the given application.
Surface Preparation:
Ensure proper surface preparation of the substrate material to promote strong adhesion between the TBC and the underlying blade material. Techniques such as grit blasting and chemical etching can be employed to improve surface roughness and cleanliness, enhancing coating adhesion.

A cooling system plays a crucial role in to enhance the heat transfer and overall performance of the coated blades by mitigating thermal stresses, reducing metal temperatures, and increasing blade longevity.These latter can impacts serval factors:
Temperature Reduction:
cooling involves the ejection of cool air through small holes or slots in the blade surface. This cool air forms a protective layer, which insulates the blade surface from the hot gases flowing over it.
As a result, the temperature of the blade surface is significantly reduced,

preventing thermal degradation and extending the operational lifespan of the blade.

Heat Transfer Enhancement:

By creating a cooler boundary layer on the blade surface,the cooling system enhances convective heat transfer away from the blade. This increased heat transfer helps dissipate heat more effectively, preventing localized hot spots and reducing thermal gradients within the blade material.

Consequently, the blade is better able to withstand thermal stresses and maintain structural integrity under high-temperature operating conditions.

Improved Efficiency:

Lowering the surface temperature of the blade reduces the temperature difference between the blade and the hot gases passing through the turbine. This reduction in temperature difference, known as the "delta T," leads to lower thermal losses and improved thermodynamic efficiency of the turbine.

Consequently, the turbine can generate more power for a given amount of fuel input, resulting in improved overall performance and energy efficiency.

General Conclusion

The objective of our work was to investigate the temperature distribution on gas turbine blades coated with thermal barrier coatings (TBC) and cooled with nano-fluid using ANSYS simulation.By achieving this, we aimed to enhance the understanding of thermal management in gas turbines, which is crucial for improving their efficiency and longevity.

To complete our project, we briefly introduced the fundamental concepts of thermal barrier coatings and nanofluid cooling. This introduction provided the necessary background for understanding the mechanisms by which TBCs and nano-fluid can enhance thermal performance in gas turbines.

Then we have given a general overview of the simulation setup and methodologies used in ANSYS. This included the selection of materials, boundary conditions, and the specific parameters for nanofluid cooling. By detailing the simulation process, we ensured a clear and replicable methodology for future research.

For this realization, we have become adept at using ANSYS for complex thermal simulations. This involved not only mastering the software's technical aspects but also developing a deeper understanding of thermal dynamics in high-temperature environments.

While our project has made significant strides in demonstrating the potential of nanofluid cooling combined with TBCs, there are still many areas that require further exploration. These include optimizing the composition and concentration of nanofluids, as well as the long-term durability of TBCs under cyclic thermal loads.

At this stage, our results indicate that nanofluid cooling can effectively reduce the temperature of turbine blades, potentially leading to increased efficiency and reduced wear. However, the exact impact on turbine performance and longevity needs more comprehensive validation through experimental studies.

Moving forward, our roadmap includes conducting experimental validations of our simulation results, exploring different nanofluid compositions, and investigating the effects of various TBC materials. This will help in refining the simulation models and ensuring their real-world applicability.

Iorder to continue working on this project we have to become aware of the advancements in nanofluid technology and TBC materials. Keeping abreast of the latest research will be crucial for improving the accuracy and relevance of our simulations.

Several other areas such as the network, remote access to databases and their manipulations, and security implementation are also critical for the progression of our project. Efficient data management and secure access to simulation data will enhance collaborative efforts and facilitate smoother project execution.

In conclusion, our work lays a solid foundation for further research into the thermal management of gas turbines. By leveraging the capabilities of ANSYS and focusing on innovative cooling techniques like nanofluids, we have opened new avenues for enhancing turbine performance. Future work will build on these findings to develop more efficient, durable, and reliable gas turbine systems.

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Abstarct

Gas turbine blades play an important role in the performance and efficiency of gas turbine engines used in various industrial and aerospace applications, positioned to play a pivotal role in facilitating the global transition towards renewable energy sources.

However, the harsh operating conditions, characterized by high temperatures and thermal gradients, pose significant challenges to blade durability and service life. To address these challenges, thermal barrier coatings (TBCs) and nanofluid cooling have been extensively employed to provide thermal protection and enhance blade cooling effectiveness.

This thesis investigates the thermal performance of gas turbine blades equipped with TBCs and nanofluid cooling using computational fluid dynamics (CFD) simulations with Ansys software.

The study focuses on understanding the complex interactions between fluid flow, heat transfer, and coating materials to optimize blade. The research methodology involves geometric modeling of gas turbine blade configurations, application of TBCs, and incorporation of nanofluid cooling. Through systematic numerical simulations, the thermal behavior of the blades is analyzed under various operating conditions and design parameters.

Results indicate that TBC thickness, material properties, and nanofluid cooling parameters significantly influence blade temperature distribution and heat transfer rates. The CFD simulations reveal insights into the effectiveness of different cooling strategies and their impact on blade performance. The findings contribute to the advancement of gas turbine blade design by providing guidelines for optimizing TBCs and film cooling techniques to enhance thermal protection and prolong blade service life.

In conclusion, this thesis offers valuable insights into the thermal management of gas turbine blades, shedding light on the intricate interplay between fluid dynamics, heat transfer, and coating materials. The research outcomes have implications for improving the efficiency, reliability, and sustainability of gas turbine engines in various industrial and aerospace applications.

keywords: Gas turbine blade, Thermal barrier coating, Tbc, Yttria-Stabilized Zirconia, Cooling, Nano-fluid, Temperature distribution, Cfd.

مُلخّص

تلعب شفرات التوربينات الغازية دورًا مهمًا في أداء وكفاءة محركات التوربينات الغازية المستخدمة في مختلف التطبيقات الصناعية والفضائية، وهي مهيأة للعب دور محوري في تسهيل الانتقال العالمي نحو مصادر الطاقة المتجددة. ومع ذلك، فإن الظروف التشغيلية القاسية، التي تتميز بدرجات حرارة عالية وتدرجات حرارية، تفرض تحديات كبيرة على متانة الشفرات وعمرها الافتراضي.

لمواجهة هذه التحديات، تم استخدام طلاءات الحواجز الحرارية (TBCs) والتبريد بالسوائل النانوية بشكل واسع لتوفير الحماية الحرارية وتعزيز فعالية تبريد الشفرات. تبحث هذه الأطروحة في الأداء الحراري لشفرات التوربينات الغازية المجهزة بـ (TBCs) والتبريد بالسوائل النانوية باستخدام محاكاة ديناميكيات السوائل الحسابية (CFD) باستخدام برنامج (Ansys) .

تركز الدراسة على فهم التفاعلات المعقدة بين تدفق السوائل، نقل الحرارة ومواد الطلاء لتحسين الشفرات. تشمل منهجية البحث النمذجة الهندسية لتكوينات شفرات التوربينات الغازية، (TBCs) ودمج التبريد بالسوائل النانوية. من خلال المحاكاة العددية المنهجية.

تشير النتائج إلى أن سمك (TBCs) ، خصائص المواد، ومعايير التبريد بالسوائل النانوية تؤثر بشكل كبير على توزيع درجة حرارة الشفرات ومعدلات نقل الحرارة. تكشف محاكاة (CFD) عن رؤى حول فعالية استراتيجيات التبريد المختلفة وتأثيرها على أداء الشفرات. تساهم النتائج في تقدم تصميم شفرات التوربينات الغازية من خلال تقديم إرشادات لتحسين (TBCs) وتقنيات التبريد بالفيلم لتعزيز الحماية الحرارية وإطالة عمر الشفرات.

في الختام، تقدم هذه الأطروحة رؤى قيمة حول إدارة الحرارة لشفرات التوربينات الغازية، مسلطةً الضوء على التفاعل المعقد بين ديناميكا السوائل،

انتقال الحرارة ومواد الطلاء. نتائج البحث لها تأثيرات على تحسين الكفاءة، الموثوقية والاستدامة لمحركات التوربينات الغازية في مختلف التطبيقات الصناعية والفضائية.

الكلمات المفتاحيّة: شفرة توربينة الغاز، ةـث (طلاء الحاجز الحراري)، زيركونيا مستقرة بالإتريا، التبريد، سائل نانوي، توزيع درجات الحرارة، الديناميكا الحسابية للسوائل.

Résumé

Les aubes de turbines à gaz jouent un rôle important dans la performance et l'efficacité des moteurs de turbines à gaz utilisés dans diverses applications industrielles et aérospatiales, étant positionnées pour jouer un rôle central dans la transition mondiale vers les sources d'énergie renouvelables.

Cependant, les conditions de fonctionnement sévères, caractérisées par des températures élevées et des gradients thermiques, posent des défis importants à la durabilité et à la durée de vie des aubes. Pour relever ces défis, des revêtements barrières thermiques (TBC) et un refroidissement par nanofluide ont été largement utilisés pour fournir une protection thermique et améliorer l'efficacité du refroidissement des aubes.

Cette thèse étudie la performance thermique des aubes de turbines à gaz équipées de TBC et de refroidissement par nanofluide en utilisant des simulations de dynamique des fluides numérique (CFD) avec le logiciel Ansys. L'étude se concentre sur la compréhension des interactions complexes entre l'écoulement des fluides, le transfert de chaleur et les matériaux de revêtement pour optimiser les aubes.

La méthodologie de recherche implique la modélisation géométrique des configurations des aubes de turbines à gaz, l'application de TBC et l'incorporation du refroidissement par nanofluide. Grâce à des simulations numériques systématiques, le comportement thermique des aubes est analysé dans diverses conditions de fonctionnement et paramètres de conception. Les résultats indiquent que l'épaisseur des TBC, les propriétés des matériaux et les paramètres de refroidissement par nanofluide influencent significativement la distribution de la température des aubes et les taux de transfert de chaleur. Les simulations CFD révèlent des informations sur l'efficacité de différentes stratégies de refroidissement et leur impact sur la performance des aubes. Les conclusions contribuent à l'avancement de la conception des aubes de turbines à gaz en fournissant des directives pour optimiser les TBC et les techniques de refroidissement par film pour améliorer la protection thermique et prolonger la durée de vie des aubes.

En conclusion, cette thèse offre des perspectives précieuses sur la gestion thermique des aubes de turbines à gaz, en mettant en lumière l'interaction complexe entre la dynamique des fluides, le transfert de chaleur et les matériaux de revêtement. Les résultats de la recherche ont des implications pour l'amélioration de l'efficacité, de la fiabilité et de la durabilité des moteurs de turbines à gaz dans diverses applications industrielles et aérospatiales.

mots-clés: Aube de turbine à gaz, Revêtement barrière thermique, TBC, Refroidissement, Nanofluide,Distribution de température, CFD.