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**MODELING AND ANALYSIS OF TURBINE
BLADE'S CREEP USING COMPUTATIONAL
FLUID DYNAMICS**

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Master's Thesis

Supervisor

Asst. Prof. Dr. Yaser ALAIWI

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INVESTIGATION OF THE CREEP OF TURBINE BLADE BY COMPUTATIONAL FLUID DYNAMICS (CFD)

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XXXXXXXXXX

DEDICATION

I dedicate this humble research to my dear parents who have done everything in their power since my childhood to push me forward for educational attainment. Although they are no longer of this world, their memories continue to regulate my life. As well as my beloved Brothers and Sister who have devoted their efforts to creating the appropriate environment and creating an encouraging atmosphere to continue research and analysis, as well as to every researcher looking forward to collecting information, which I tried as much as possible to collect as much as possible how much can be related to the topic of research.



PREFACE

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ABSTRACT

MODELING AND ANALYSIS OF TURBINE BLADE'S CREEP USING COMPUTATIONAL FLUID DYNAMICS (CFD)

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The global population is on a steady rise, while our resources are dwindling at an alarming rate. In order to cater to the world's energy demands, it is imperative that we transition to a device that boasts optimal efficiency. The turbine is a well-suited option in this regard, with gas turbines serving as a prime example of such machinery. Creep is a phenomenon characterized by the gradual and time-dependent inelastic deformation that occurs under mechanical loading and elevated temperatures. The phenomenon of creep is often accompanied by various microstructural rearrangements, such as dislocation motion, microstructure aging, and cavitation at grain boundaries. In recent decades, numerous numerical and experimental studies have been conducted to enhance the understanding of creep behavior in structures subjected to elevated temperatures. The three primary subjects under consideration are the creep constitutive relationship, the creep damage evolution equation, and the method for predicting creep life.

Previous research has focused on enhancing the efficacy and quality of gas turbines through various methods, including film cooling, coating, and blade curvature. These techniques aim to safeguard the turbine blades from the extreme temperatures of up to 1400°C within the turbine, thereby prolonging their lifespan. However, the impact of these methods on the engine's efficiency has not been a primary consideration in prior research. The objective of this study is to improve the efficiency of gas turbines. The efficacy of the turbine blade can be evaluated based on the temperature applied to the turbine after coating.

The present study involves a simulation that utilizes defined values of temperature and pressure to conduct a computational fluid dynamics (CFD) analysis on blade construction. The meshing of the blade will be performed using ANSYS software, and finite element method (FEM) calculations will be conducted. The results obtained from these calculations, pertaining to the temperature and CFD analysis within the gas turbine of varying numbers of blades, will be compared to determine the optimal efficiency point.

Keywords: Computational fluid dynamics (CFD), ANSYS, Gas Turbine Blades.



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ABBREVIATIONS

CFD	:	Computational Fluid Dynamics
3D	:	Three Dimensional
Variable	:	Description
C _p	:	Constant Pressure Specific Heat
g _{x,}	:	Gravitational Acceleration In X, Y, Z Directions
q _V	:	Volumetric Heat Source
u	:	Velocity Component in X-Direction
v	:	Velocity Component in Y-Direction
w	:	Velocity Component in Z-Direction

LIST OF SYMBOLS

C_p	:	Constant Pressure Specific Heat
h	:	Enthalpy
k	:	Thermal Conductivity
p	:	Pressure
μ	:	Viscosity
ρ	:	Density



1. INTRODUCTION

1.2 INTRODUCTION

An internal combustion engine called a gas turbine uses gas as the working fluid to turn a turbine. They may be utilized for a huge variety of functions, including operating pumps, compressors, and generating electricity in the utilities sector in industrial facilities in addition to powering aircraft of various kinds [1]. Given their weight and size, they could generate a significant amount of energy. Turbine, combustion chamber, and Compressor are the three components of a combustion gas turbine, and they are all located on the same shaft. The air intake allows cool air to enter the compressor. The air is under increased pressure as a result of the compressor, which drives it into the combustion chamber. The compressor results in a reduction in air volume and a rise in pressure. The fuel would then be fed by nozzles into the combustion chamber, where the compressed air is combined with the fuel. The volume and temp of the gas are then increased when the fuel-air combination ignites under a constant pressure situation. The turbine portion receives this vast amount of high pressure air, which is sent there where it expands and causes the shaft to revolve. This shaft rotation propels the compressor to continuously pull up additional air [2].

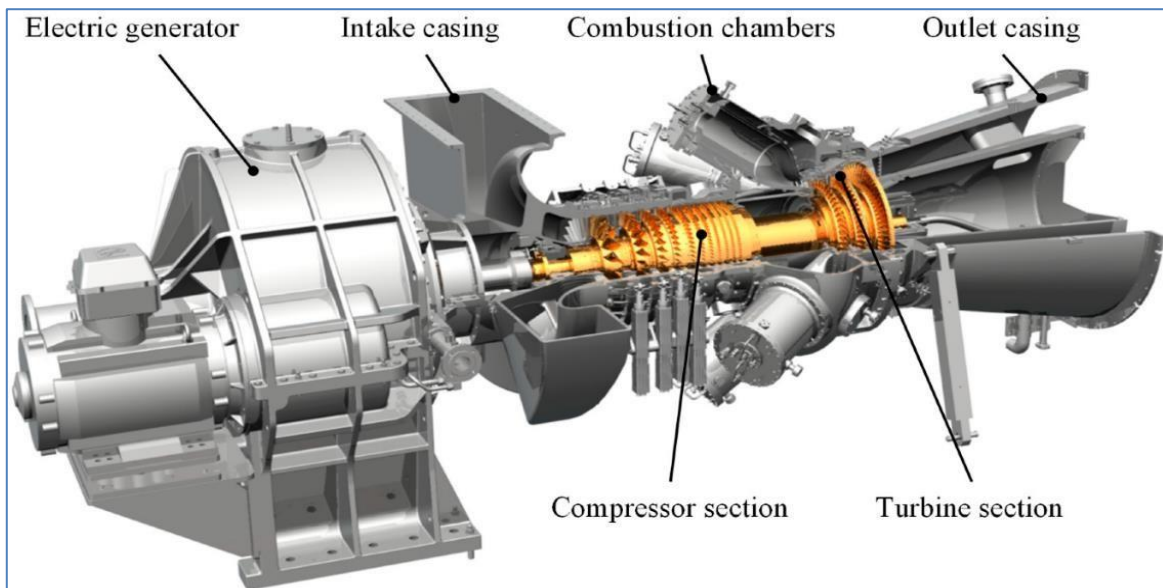


Figure 1.1: Gas Turbine Construction [3].

Gas turbines come in one- and two-shaft varieties. The latter features two shafts with varying rates of rotation. The compressor and the turbine that powers it are on one shaft, while the power turbine which drives the external load is on the opposite shaft. Alternatively, one shaft may house the turbine segments and high-pressure compressor, while the other would house the external load, turbine, and low-pressure compressor [4]. Numerous industrial applications benefit from the ability to drive the load at varying speed provided by the two-shaft design. load, turbine, and compressor are all mounted on a single shafts that rotates at a fixed speed in single-shafts turbines. This set-up has been utilized to power both large and small generators for utility purposes [5].

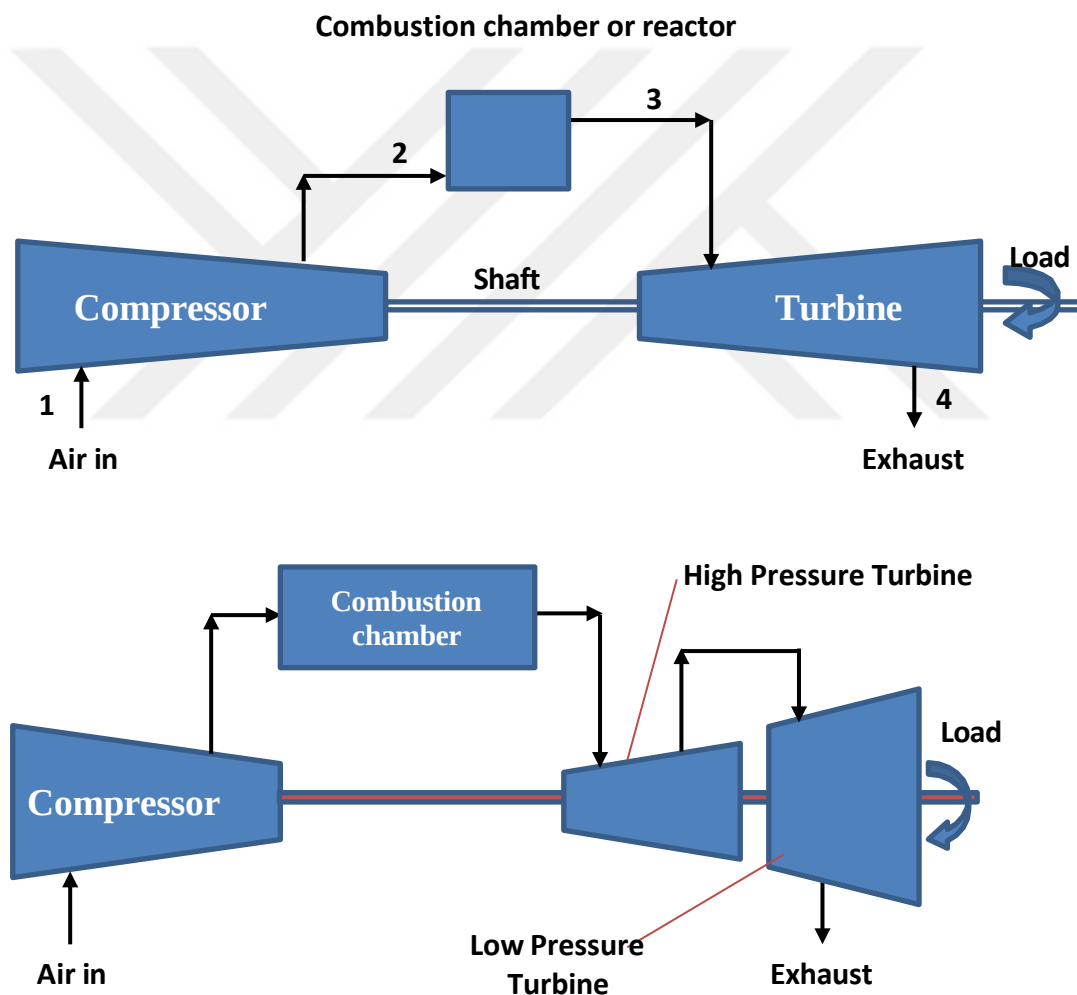


Figure 1.2: Gas Turbine Cycle Diagram With A Single and Dual-Shaft Design [6].

The Brayton cycle seems to be the basis of the gas turbine [7]. The following processes are included in the cycle:

- a. Isentropic Compression
- b. Additional constant for pressure heating
- c. Isentropic Expansions
- d. Rejection Constant for Pressure Heating

1.3 GAS TURBINE KINDS

Simple gas turbines may be split into two categories [8]:

1.3.1 Frame Kind Heavy Duty Gas Turbines

In contrast to aviation designs, these gas turbines have heavier frames, bearings, and blades. They are also significantly more integrated with the machinery that recovers leftover energy from the machines they power, which is frequently an electric generator (largely heat) [9].

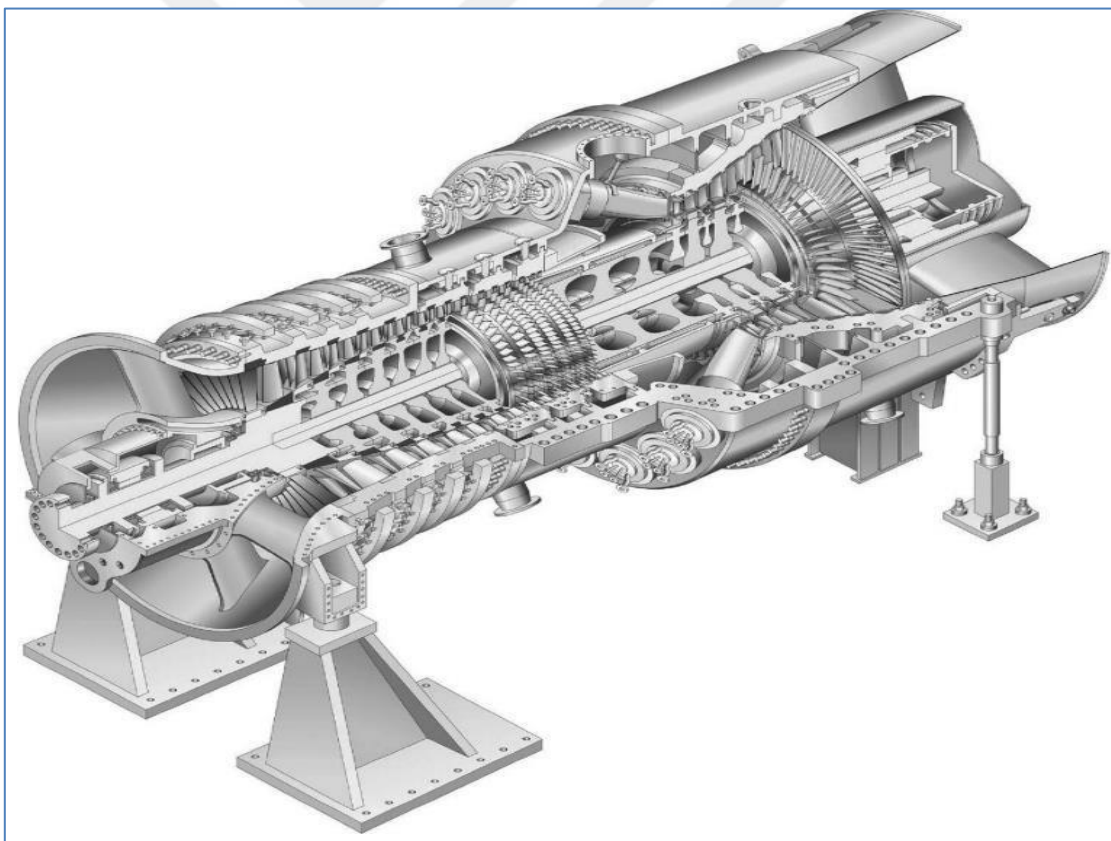


Figure 1.3: Heavy Duty Gas Turbines [10].

1.3.2 Aero-derivative Gas Turbines

As their name implies, aero-derivative gas turbines seem to be modifications of the gas turbines utilized in aircraft ("jet" engines). Industrial gas turbines have been created with the expectation that they will be used on the ground. In aviation, in which the power generated by the turbine is utilized to power a compressor, aero-derivative gas turbine technique is frequently employed. Through the employment of an exhaust nozzle, the hot air that leaves the turbine is propelled into the atmosphere to provide thrust [11].

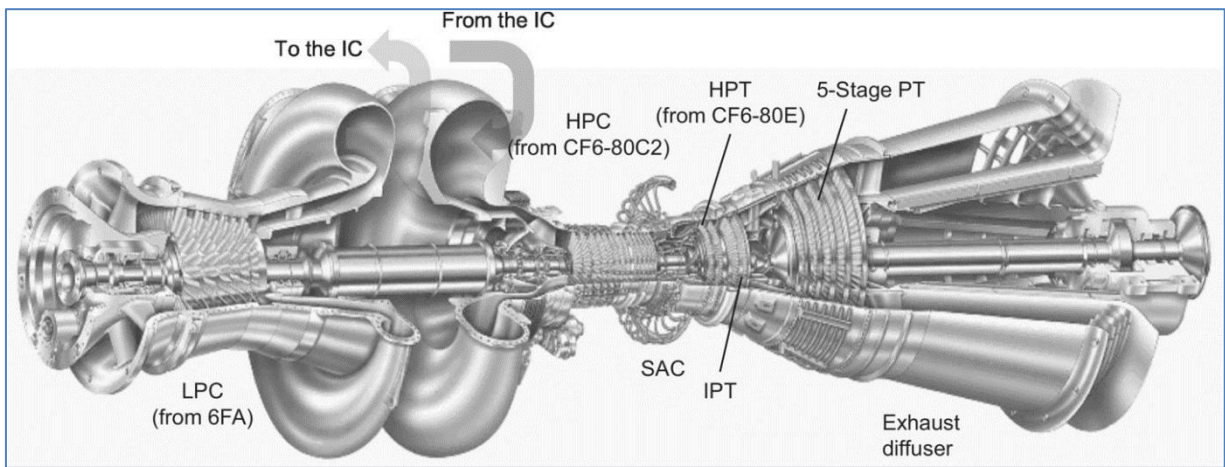


Figure 1.4: Aero-Derivative Gas Turbines [12].

1.4 MAIM GAS TURBINE COMPONENTS

1.4.1 Compressor

Axial designs with up to 19 steps or centrifugal designs with one or two impellers are also possible for compressors. Early gas turbines utilized centrifugal compressors, were very inexpensive, had simple designs, but were unable to create high pressure ratios. Today, tiny turbines use these earlier gas turbines instead.

The fundamental constituents of a centrifugal compressor comprise a static casing that houses a rotating impeller, which impels air at a considerable velocity, and a sequence of immobile diverging pathways where air is decelerated, thereby augmenting static pressure. The impeller disc's vanes turn the air rapidly around after being drawn into the impeller eye. The air is forced toward the impeller's

outer edge by centrifugal force. When air enters the diffuser casing, its high velocity is lowered and its pressure rises [13].

Due to their greater flow rates and efficiency, axial flow compressors are more often used in the production of electricity. Every stage of the axial flow compressor is made up of a row of rotor blades, following by a row of stator blades. The rotor blades first accelerate the working fluid, which is then decelerated in the passageways of the stator blades, in which the kinetic energy transmitted in the rotor is transformed into static pressure. To get the needed overall pressure ratio, the operation is done as many times as necessary. The volume of the air reduces as it is compressed. To ensure a consistent through-flow velocity, it is necessary to reduce the area of the annular passage, resulting in shorter blades at higher pressures [14].

1.4.2 Combustion Chamber

Without a combustion chamber, a gas turbine linked to a compressor would not provide sufficient power to drive the compressors, dissipate friction, and still have power to drive other machinery. Burning fuel in the combustion chamber produces the additional energy needed [15].

To achieve the separation of the two air streams emanating from the compressor, it is necessary to decelerate the air initially. The region in which fragmented fuel is introduced and undergoes combustion through a flame that is stabilized by a turbulence-generating obstruction is fed from the smaller flow at its center. To achieve a suitable temperature for the turbine intake, the larger and cooler stream is introduced into the chamber through perforations along a "combustion liner," which is a type of shell.

The majority of combustors have a reverse flow configuration. According to this design, air enters the turbine via the space between the hot gas line and the combustor container. The air then moves across this space before entering the combustion area at numerous points of entrance. When utilized for big units, the single container features a ring of nozzles or many fuel nozzles [16].

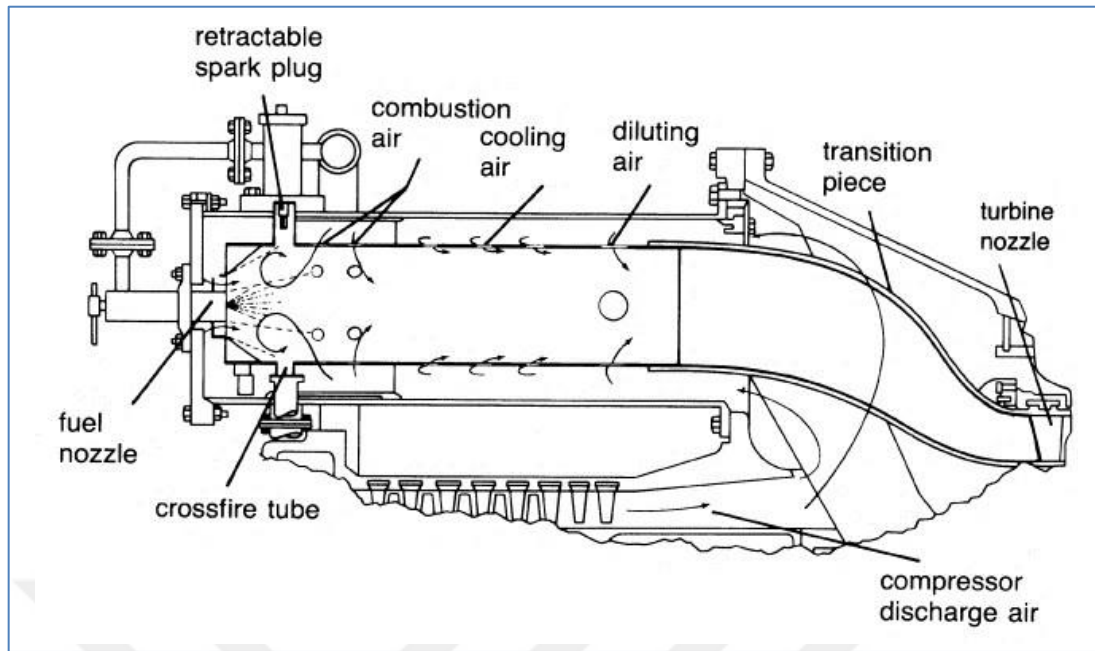


Figure 1.5: Combustion Chamber [17].

1.4.3 Turbine

Air exits the combustion chamber via a transition piece, which is a duct or tunnel. It lasts long sufficiently ensure, which the hot air is evenly distributed and prevent hot pockets. A number of discs attached to the shaft and rotating with it make up the turbine. The turbine might be of the response or impulse kind. When an air jet travelling at a high speed from a nozzle contacts a rotor blade, it rotates the blade and generates power. In the response kind, the rotor rotates in the opposite direction from the air jet as the air expands thru the rotor blades. Rotating and stator blades are used in the majority of reaction turbines. A jet of fast-moving air is directed towards the rotor blade by the stator blades. The rotor rotates as a result of the jet striking it. The air then expands, applying force to keep the rotor rotating [18].

1.5 CREEP

Minimizing the creep caused by operating loads and high temperatures is a significant difficulty for turbine design, particularly for turbine blades. Continuously sought for higher operating temperatures to boost efficiency come at the expense of increasing creep rates. Therefore, a variety of techniques have been used in an effort to maximize performance

while minimizing creep, with high performance coatings and single crystal superalloys proving to be the most effective [19]. These technologies minimize deformation caused by the diffusional flow processes, dislocation climb, and dislocation glide, which may be generally categorized.

Protective coatings give oxidation and corrosion protection as well as heat insulation for the blade. Aluminides or MCrAlY alloys (M is often Fe or Cr) are frequently utilized as oxidations/corrosion resistant coatings (bonding coats) and thermal barrier coatings (TBCs), which are frequently stabilized zirconium dioxide-based ceramics. Utilizing TBCs restricts the superalloy substrate's exposure to high temperatures, which lowers the diffusivity of the alloy's active species (usually vacancies) and vacancy creep and lessens dislocation. Blade temperatures were reported to be reduced by up to 200 °C (392 °F) with a coating of 1-200 µm [20]. Bond coatings are used to provide both enhanced TBC adhesion and substrate oxidation resistance. They are applied directly to the substrate's surface via pack carburization. Al₂O₃ is created on the TBC-bonding coat interfaces by the Al from the bonding coats, providing oxidation resistance while also causing an undesired interdiffusion (ID) zone to develop between the substrate and bonding-coat [21]. The benefits of the ID zone's oxidation resistance exceed its disadvantages since it prolongs blade life and reduces efficiency losses brought on by accumulation on the blades' exteriors [22].

Due to their composition and resulting microstructure, superalloys based on nickel have increased strength and creep resistance. The coherent Ni₃(Al,Ti) gamma-prime (γ') phases are precipitated as a uniform dispersion by alloying the gamma (γ) FCC nickel with aluminium and titanium. The finely scattered "precipitates" obstruct dislocation movement and provide a threshold tension, raising the stress necessary for creep to start. Additionally, it is an organized L12 phase, dislocations have a tougher time passing through it [23]. Furthermore, to increase creep strength, refractory substances like ruthenium and rhenium may be added to solid solutions. By reducing the dispersion of the gamma prime phase, the incorporation of these components keeps the creep resistant intact, strength, and fatigue resistant [24]. Significant advancements in creep resistance have also been made because of the creation of single crystal superalloys. Single crystals don't experience Coble creep since there are no grain boundaries, which leads to fewer modes of deformation and a slower creep rate [25]. At room temp, where strength is governed by the Hall-Petch association, single

crystals have much lower yield stresses while having reduced creep at high temperatures. The design parameters must be carefully optimized to prevent a reduction in low temp yield strength while limiting high temperature creep.

1.6 PROBLEM STATEMENT

Under the impact of applied stress, gas turbine components working at high temps distort over time. A creep rupture mechanism eventually leads to fracture as a result of the buildup of such distortion. Blade creep damage is identified as the primary factor contributing to the reduction in blade lifespan in base-loaded gas turbines. The assessment of vital component design for high-temperature applications necessitates taking into account of deformation and damage processes. In this regard, engineering calculations require an understanding of the creep-rupture parameters of the material utilized by the structure. The creep-rupture characteristics are determined by utilizing the outcomes of a sequence of creep tests conducted under different constant temperature and constant load conditions. The extension of the remaining lifespan of essential components, such as gas turbine blades, and the evaluation of blade creep and fatigue loading behavior under severe operating conditions, are vital factors in the extension of power plant lifespan. The deformation characteristics of materials under creep can be described through a range of constitutive equations, which span from fundamental phenomenological models to intricate physically grounded formulations [26]. It is challenging to identify a single constitutive equation that can effectively describe the creep deformation characteristics of all materials over their entire temperature range of application. The predictive capacity of a constitutive equation with respect to secondary, primary, and tertiary creep deformation is contingent upon the material properties and distribution of data for a given application. Certain model equations and fitting approaches may not be suitable for the prediction of the long-term creep strength behavior of alloys [20].

1.7 AIMS AND OBJECTS

The aim of the work is to investigate the thermal appearance of the turbine blade without a thermal barrier coating, and after that the thermal appearance of the turbine blade is studied. Through intensive CFD analysis, the CFD instrument is used to generate and simulate the

flow over the turbine blade and the flow behaviors on the turbine blade and the data obtained after the simulation are compared with the observation of the effectiveness of the thermal barrier coating. However, to achieve the aim of the current study, the following objectives could be drawn down:

- i. To explore the creep issues and possible solutions that could applied.
- ii. The utilization of computational fluid dynamics (CFD) simulation to generate two-dimensional models for the purpose of examining the influence of thermal stress on the manifestation of cracks in gas turbine systems.
- iii. Making a comparison between the obtained results from ANSYS and some experimental studies that applied in the same field of study.

1.8 THESIS LAYOUT

The present thesis comprises a total of five chapters, which are outlined as follows.:

Chapter 1: Introduction: consists of background about gas turbine, types of gas turbine, and the issue faced gas turbine.

Chapter 2: Literature review related to gas turbine components, creep issue reasons and solutions with related studies of creeps in gas turbine.

Chapter 3: Numerical Modelling with CFD methods for gas turbine and some experimental works and tests that are usually used to investigate the creep.

Chapter 4: This chapter presents the outcomes derived from the utilization of the ANSYS software program, followed by a comprehensive analysis of the findings. Furthermore, a comparative evaluation is conducted between the obtained results and the experimental results.

Chapter 5: Conclusions and recommendations for the future works..

2. BASIC CONCEPT AND LITERATURE REVIEW

2.1 INTRODUCTION

There are multiple factors that contribute to the failure of blades. The factors that are taken into consideration are fatigue, creep, corrosion, erosion, sulphidation, foreign object damage (FOD), and vibration. Despite the existence of advanced design software, blade failures remain a common occurrence in compressors and turbines. Research has indicated that the most frequently dismissed components are the blades found in both the compressor and the turbine [27].

2.2 MAIN BENEFITS OF GAS TURBINES

There are many benefits for using gas turbines in different fields as following:

2.2.1 Lower Operational Cost

One of the primary parameters contributing to the popularity of gas turbines is their lower operating costs. The initial operating cost of gas turbines seems to be quite inexpensive when compared to other low-carbon emission options including renewable and nuclear energy. Consequently, gas turbines represent one of the finest solutions for producing greener electricity in addition to being cost-effective [28].

2.2.2 Efficient and Durable

Gas turbines have emerged as a viable option owing to stringent carbon emission regulations, volatile fuel prices, and a drive for high performance at low costs. Gas turbines are a cost-effective option that offers dependable performance, high efficiency, and low operational disruptions and downtime. In reality, producers of gas turbines have developed very robust turbines that need maintenance less often. [29].

2.2.3 Facilitates Distributed Power Generation

The majority of the world's power generating systems are transitioning to distributed power production. The technology used for distributed electricity is extremely adaptable and could function both independently and as a component of an integrated system. Additionally, it is preferable to small wind turbines, hydropower, solar panels, and fuel cells [30].

2.2.4 Environmentally-Friendly

One notable benefit of gas turbine power plants is their ecological neutrality. Apart from utilizing natural gas as a source of energy, they also discharge a lower amount of pollutants from their exhaust emissions in comparison to engines with internal combustion (ICE). The additional air is utilized for the process of combustion in gas turbines. Gas turbine power plants utilize a variety of gaseous fuels, such as natural gas, synthetic gases, digester gas, and landfill gas to generate electricity [31].

2.2.5 High Operational Speed And Low Lubrication Cost

In contrast to other types of engines, gas turbines require minimal quantities of lubricating oil. The operational cost experiences an immediate reduction as a result of this. Moreover, gas turbines expedite the generation of energy and power owing to their higher operational velocity. Gas turbines are known to provide advantages such as decreased operating expenses, improved service, and enhanced speed [32].

2.3 DRAWBACKS

In spite of presence many benefits for using gas turbines, there also some drawbacks relating to turbine uses such as [33], [34]:

- a. The plant must be started using either an electric motor or an internal combustion engine. The compressor should be well on its way to operational speed before the starting motor kicks in. As a result, beginning is more complicated than it is for other power plants.
- b. Once comparing gas turbine plants to reciprocating engines running at the same speed, gas turbine plants vibrate less. Nevertheless, the compressor's high frequency noise was unpleasant.

- c. Extremely hot weather severely restricts how the plant can be serviced.
- d. Because the compressor requires two-thirds of the entire power output, overall efficiency is poor.
- e. Due to high operation pressures and temps the turbine blades need unique cooling techniques. The temperatures near the turbine's entrance may reach 1100 degree centigrade to 1260 degree centigrade. They must therefore be constructed of unique alloys and metals.
- f. They cannot be used with solid fuels.

2.4 FATIGUE FAILURE

The applied stresses have not been constant in most real-world engineering scenarios, particularly for gas turbine blades. Instead, the burden varies, often in an unpredictable way. It is routinely seen that failure happens under cyclic stress situations at lower stress levels than might be anticipated. The bulk of in-service turbine blade failures are brought on by this fatigue phenomenon. As depicted in Figure 2.1, the fatigue failure mechanism is commonly divided into three distinct phases. The fracture process can be divided into three stages: primary initiation of the fracture, secondary propagation of cracks, and unstable propagation of cracks, also known as the tertiary stage [35].

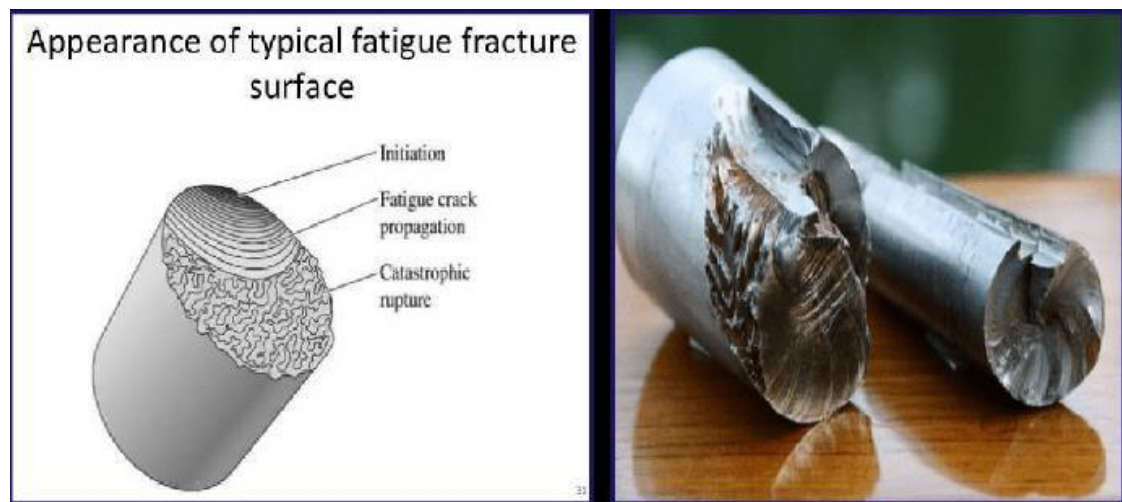


Figure 2.1: Phases of Fatigue Failures [36]

The fatigue life of a gas turbine blade is contingent upon both the material composition and the magnitude of cyclic loading. The service life of a blade can be significantly

affected by the manufacturing and processing of materials. Microstructural factors, such as variations in the alloying, size of the grains, and the existence of non-metallic inclusions, can have an effect on the fatigue life. Additionally, variables including corrosive surroundings, residual stresses, surface finish, stress concentrations, random stress variations, etc. have a significant impact on fatigue behaviour [37]. Nickel-base superalloy is the primary material used to make the gas turbine blades. Nickel-base superalloy seems to be the best material to use for turbine blade applications due to its superior micro structural stability, hot corrosion and creep resistant, fatigue and tensile strengths, and thermal stability [38], [39]. The conventional material for gas turbine hot stages, where high mechanical loads, high temps, and harsh conditions are present, is super-alloy [40]–[46].

The region of the stress/strain curve of the material that exhibits elasticity is primarily where the gas turbine blades' design loads are concentrated. The S-N curve was created to address the old approach to fatigue, which focused primarily on failure after a significant number of cycles. Low Cycle Fatigue is the term used to describe the phenomena where the fatigue life gradually decreases under greater pressures and lower cycles and eventually results in component failure [47].

It is commonly accepted that the point at which elastic and plastic strains make up equally large amounts of the total strain marks the boundary between low and high cycles fatigue (LCF and HCF), respectively [48]. To make things easier, LCF is typically thought to fail in fewer than 10⁵ cycles while HCF fails in more than 10⁷ cycles. Based on design application, it might be assumed that the intermediate range belongs to either area. It is important to keep in mind that the frequency with which a cyclic load is delivered is not very significant. alternatively, the total amount of harm sustained with each load application. It is applicable to distinguish between HCF and LCF for crucial gas-turbine components such turbine blades by figuring out what causes the cyclic loads. In contrast to HCF, which is often driven by vibration sources and the use of relatively modest loads, LCF was usually driven by pilot requirements and the use of very high loads.

2.4.1 Low Cycle Fatigue (LCF)

The cumulative strain energy per reverse would be much larger if the cyclic stresses amplitude that are applied to a component seems to be extremely high (LCF) [49]. For this purpose, under LCF, a component would spend the main of its lifetime in the secondary stage of fatigue failure, also characterized as the fracture propagation stage, and a very tiny amount of its life in the primary stage, characterized as the crack initiation stage. Most of the crucial parts of gas turbine engines, including the turbine blades, are exposed to very high cycles loading, which shortens their lifespan. The following factors contribute to the mechanical stress on these components [50]:

- a. Thermal loading and centrifugal forces.
- b. Great pressures in the casings.
- c. Thermal differences in components

2.4.1.1 Low cycle fatigue (LCF) in turbine blades

LCF is associated with substantially greater stress cycles brought on by engine starting and stopping. The loadings that the turbine blades experience while at rest are mostly caused by their own weight and are at room temp. The same turbine blades undergo intense centrifugal forces during operating as a result of the speed of rotation, and they also work at significantly greater temps [51]. Engines experience quick transitions between the two states. Starting an engine increases the temp differential and causes a significant degree of thermal stress, which then achieves a stable state throughout operation and reappears when the engine is shut off, or during cool down. The investigation revealed that the gas turbine blades employed in gas turbine engines are subjected to considerable stress due to frequent start-ups and deceleration, which has a notable effect on their lifespan. Nevertheless, owing to several other circumstances, the degree of degradation or failure of certain blades may vary. The variability of this rate is contingent upon the type of engine and is primarily ascertained by the magnitude of the loads imposed and the operational temp of the turbine blades [51]. As an illustration, the duration of a turbine blade's functional life in a diminutive engine that

functions at elevated velocities and temperatures could be as brief as 10000 hrs or less. Conversely, the duration of the identical engine's functional life when functioning at standard velocities and temperatures may be as extensive as 20000 hrs or more. According to certain case studies, turbine blades used in short-distance engines have a lifespan of as little as five years, but those used in long-distance engines have a lifespan that is commensurate with expectations.

These forces are cyclical in nature because engine power settings change. Once the engine was propelled from a standstill to its maximal rotational speed and then brought back to a halt, one full or main cycle was indeed performed. All other throttle motions result in little cycles of varied sizes. The definition of LCF in a gas turbine pertains to the loading cycles that occur due to alterations in the speed of rotation, temperature distribution within components, or the internal pressure of the engine, which are commonly induced by throttle movements [52].

Salehnasab and Poursaeidi [53], investigated the initiation and progression of fatigue fracture in CM186 LC directional solidified substance of a 1st-stage gas turbine blade through process analysis and modeling. ABAQUS software was used to conduct a finite element research to look at the fracture starting spot. According to engine situations, the stress distribution of the blade was estimated, and the propagation of the fatigue crack was then forecast using the ZENCRACK fracture mechanics algorithm. The fatigue life was also estimated in this investigation using the Paris model. Following the calculation of the stress intensity factors (KI & KII) of each mode and fracture mechanics parameters using CTOD and J-Integral techniques, the crack propagation direction was determined using the greatest energy release rate criteria. The shank area of the blade featured multiple eutectic phases, which are referred to as weak regions of the material and a region vulnerable to crack initiation, depending on experimental analysis of the broken blade and material assessments. The fracture expanded up to 1.1 mm after being started in the high localised stress zone. So even under the worst circumstances, the gas turbine could function. The blade's shank area may experience a fatigue fracture as a result of the propagating crack. Additionally, if the blades failed, the gas turbine could suffer serious damage and trip, resulting in extended outages and financial loss.

2.4.2 High Cycle Fatigue (HCF)

A critical crack size is reached in a highly stressed area of a component, or the applied stress and crack size surpass the material's fracture toughness, causing fatigue failure. The steps of fracture initiation and sub-critical crack propagation are necessary to reach any of these states. While in an LCF system components spend most of their life in the fracture propagation phase, under an HCF system the crack initiation process is frequently the most time-consuming. The failure of a fracture that was started by an LCF might be hastily propagated by high frequency load-cycles (HCF) and low amplitude [51].

Engine design significantly influences HCF. When a component in HCF fails, it usually seems to do so because of being stressed repeatedly (more than 10⁷ times). A variety of things, often referred to as drivers, may overload components at high frequencies [54].

2.4.3 Thermo-Mechanical Fatigue

A combination of external stresses and tensile loads and cyclic compressive created by temperature gradients across components results in thermomechanical fatigue damage. For turbine blades, and especially cooled blades, this impact is very important. An uncooled HP turbine blade, for instance, seems to have no residual stresses and is at a constant temp prior to the initial engine start. The blade heats up quickly as the engine starts, but it takes longer for the core to get to operational temp. As a result, there are too many compressive pressures, especially at the plastically material deformation and leading edge, to release the pressure [55].

Because of the previous compressive deformation, the outer surface enters tension when the blade core achieves steady state temp. This tensile loading is increased by the centrifugal force on the blade. The outer surface contracts as the throttle are deferred because the centrifugal forces are reduced and the outer surface cools more quickly than the core. The core, which keeps the outer surface under tension, opposes this contraction. There is still a tensile tension in many components outside surfaces

after the engine is turned off and has warmed to room temperature. This procedure increases the amount of tensile stress cycle that the blade experiences, especially in the limited areas like the edges of trailing and leading where temp changes happen the fastest [37].

Therefore, any change in temperature causes the blade to go through a stress sequence. The temperature gradient that is created in the blade and which is a result of the throttle movement rate determines the size of the load that is applied. Therefore, it is best to shift the throttle as gently as possible for a long engine life. Because of differences in temp and the coefficient of expansion, the thermal gradient would result in a stress field that changes over the radius [56].

The onset and spread of fractures in a material because of alternating heating and cooling is known as thermal fatigue. A non-uniform temperature distribution is nearly invariably the result of this heating and cooling, and that in turn leads to cyclic thermal stress. Naturally, this thermal stress causes thermal-fatigue cracking. In railroad locomotives, diesel engine pistons, steam and gas turbine blades, thermal fatigue may (and frequently does) develop. Engineers are most concerned about the thermal-fatigue issue because it may start fractures in aviation gas turbine blades. To maximize efficacy, thrust, and economy, contemporary gas turbines have been operating at ever higher temps. Additionally, service times are being extended. These are the conditions that tend to make the failure mechanism of blades in gas turbine, thermal fatigue, predominate [57].

2.5 CREEP FAILURE

Creep was a phenomenon characterized by the gradual deformation or movement of a solid material over an extended period of time, which occurs when the material is subjected to prolonged exposure to high stress levels which fall below its yield strength. Materials that undergo prolonged exposure to high temperatures and are in close proximity to their melting point exhibit a higher susceptibility to creep. The phenomenon of creep tends to exacerbate with an increase in temperature. [58]. Three creep phases are shown in Figure 3.2.

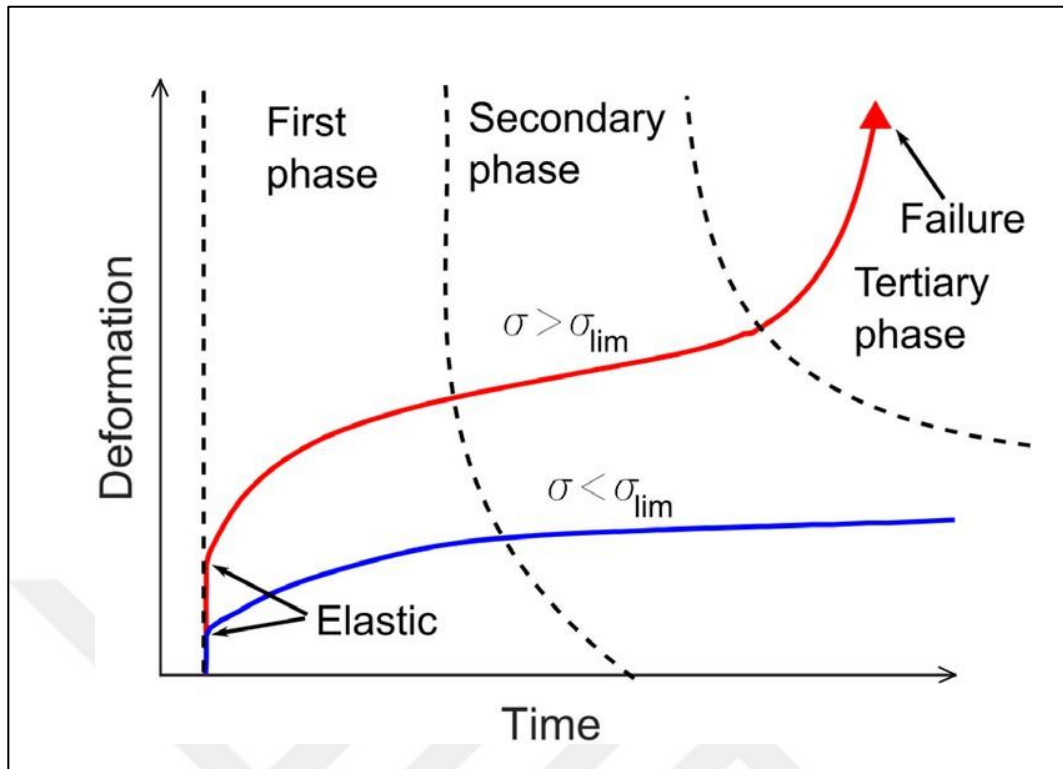


Figure 2.2: The Creep Phenomenon Can be Divided into Three Distinct Stages. [59]

The initial phase exhibits a rapid and diminishing extension rate, which holds significance for designers as it impacts the total extension achieved within a given timeframe and consequently affects the clearances selected. During the Secondary Stage, there is evidence of creep occurring at a consistent rate. It is advised that the components that often fail because of creep be performed in secondary stage since this is the critical portion of the curve for most applications. The rate of creep to failure accelerates in the tertiary stage. It is best to avoid this stage during operations since it might be difficult to forecast when a stage will go from the Secondary to the Tertiary Stages [60].

Numerous variables, including the characteristics of the material, period of exposure, exposure temp, the imposed structural stress, etc., affect how quickly this deformation (creep) occurs. Based on the severity of the applied stress at high temps and how long it lasts, the creep may increase to the point where a component is no longer able to carry out its intended function. The blades of a gas turbine seem to be the parts that experience creep the most. When a turbine blade creeps, it will meet the housing and

eventually break. On application of stress, creep deformation may not happen abruptly. Instead, persistent stress leads to strain accumulation. A "time-dependent" deformation is creep. Creep is most prominent in the airfoil's mid span that encounters the maximum temp and impacts turbine blades' hot sections and the last stages of high-pressure proportion compressors. Because it causes rotor tip clearances to gradually decrease, creep strain is important. High strains and temps in the disc rim area may also cause time-dependent plastic deformation there [61].

2.5.1 Creep Failure of Gas Turbine Blade

The point of the turbine component with the maximum temp is often thought to be the turbine blades, particularly HPT 1st-stage blades [62]. The combustion chamber's exhaust gases are directed towards the turbine, where they come into contact with the airfoils of the turbine blades, with a particular emphasis on the regions near their tips. In order to maximize the energy output of the hot stream of combustible gases emitted from the nozzle, it is widely acknowledged that it is necessary to minimize the distance between the blade tips and the adjacent shrouds (casing). Creep is a phenomenon that is commonly observed in high temperature and high stress operating conditions. It is typically identified by the elongation or deformation of blades, which is often referred to as blade stretch. The "tip-rub" phenomenon, which is shown in Figure 2, is caused by the turbine blades' tendency to creep while operating under unusual circumstances at high temperatures. The rubbing frequently causes the blade tip to be negatively impacted, necessitating engine repairs, and sometimes necessitating the replacing of non-rotating shroud and blades. Blades are stretched at regular intervals and the surplus length is cut to maintain the appropriate distance between the shroud and tip so as to avoid damages like creep [63]. This is necessary to prevent failures of the gas turbine blades owing to creep in addition to get the most work possible out of the gases at extreme temps [64]. When the accumulated tension exceeds the predetermined level, the blades are either eliminated or replaced. It is crucial that the gas turbine engine be operated within normal temp ranges and that the blades are examined often enough according to the design time intervals to avoid creep failures. By contacting the turbine blade tips with the nearby shroud, turbine blade creep can occasionally result in the

loss of coating from the tip area. This exposes the underlying super alloy substance to corrosive and oxidizing gases, that might eventually result in the corrosion-related turbine blade's failure.

It is well known that turbine blades should never, under normal circumstances, be worked at temps that are excessive for an extended length of time. Extremely brief durations of exposure to excessive temperatures are allowed, such as during start-up or in emergency circumstances. Such exposure has to be well managed, and sample blades must be examined metallographically for any potential damage. It is often considered that the blades were damaged, and replacing is necessary if the microstructure was thus deteriorated by exposure to high temperatures. Metallurgical tests may be used to identify creep exposure; typical markers include the coarsening of gamma prime precipitates and the development of void holes at grain boundaries. Greenfield [65] has information on creep. Often, a lack of cooling might be linked to creep problems. This loss may be the result of a defect in quality control (such as clogged cooling channels) or an obstruction in or issue with the cooling airflow.

The fact that gas turbine blades have been used at extreme temps for longer periods of time makes it essential to comprehend the behaviour of a turbine blade material during creep deformation in order to prevent failures brought on by the creep mechanism.

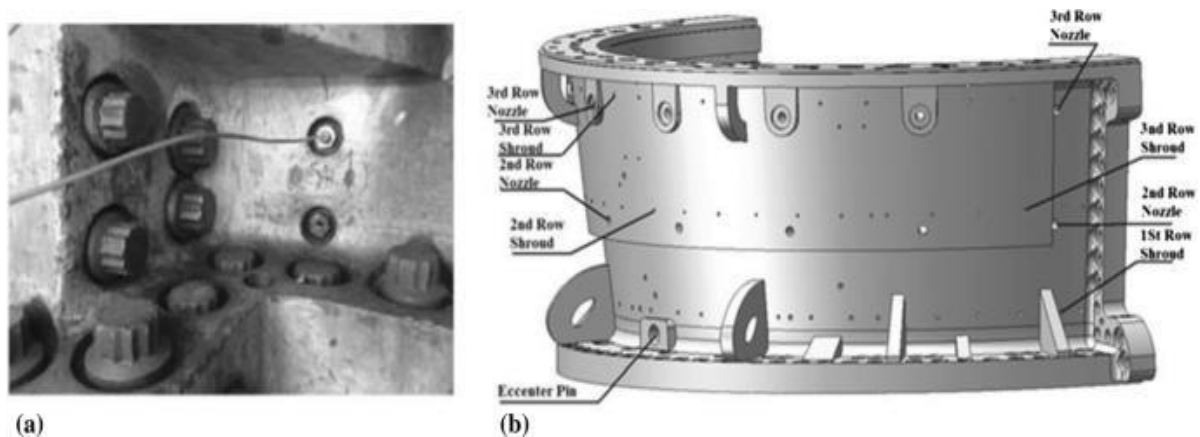


Figure 2.3: Turbine Blade Cracks Related to Creep [66].

A turbine casing's total lifespan was projected by Poursaeidi et al., [67] based on their assessment of the creep-fatigue crack formation on the outside surfaces of the turbine casing.

Nondestructive tests were used to locate, measure, and establish the direction of the fracture. Thermography-measured temperature distribution served as the FEM simulation's boundary condition. The casing stress distribution according to the actual turbine cycles was computed using the ABAQUS program. The ZENCRACK algorithm was used to forecast the development of both fatigue and creep cracks. The fatigue life was calculated using the Paris formula, and the creep life was predicted using the time-dependent Paris formula. The study revealed that the crack stress intensity variable (K) and the time-dependent stress intensity variable (Ct) exhibit a plateau effect, ceasing to increase beyond the values of the fatigue threshold stress intensity variable (K_{th}) and the creep crack mechanics variable (C^*t), respectively. This phenomenon occurs after a specified duration has elapsed.

2.6 CORROSION FAILURE

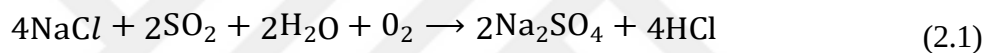
The gas turbine blades work at high temperatures and are subjected to corrosive environments. The use of a broad variety of fuels, particularly heavy fuels, is made possible by gas turbine engines, although these fuels may include pollutants includes molybdenum, lead, vanadium, calcium, potassium, sodium, and sulfur. Gas turbine blades are affected by severe hot corrosion issues as a result. Before introducing the fuel to the gas turbine engine, it is essential to verify that it has been adequately treated to an appropriate quality. When fuel is delivered by barges, fuel often becomes contaminated with salt water, and the airborne contaminants that enter the intake air depending on where the turbine is located. Additionally, salt may enter the gas turbine via the air. Although this issue is particularly acute in gas turbines used on ships and in coastal areas. Sulfur and sodium are often present as active components in the form of salts in atmospheric pollutants from marine ecosystems, pollution from industry, and forest fires. These air pollutants may cause alkali metal sulphates to build on the blade surfaces, leading in a hot corrosion damage [68]. According to certain research, heated corrosion brought on by airborne salt that is delivered into the gas turbine engine with air may also have an impact on the turbine blades used in onshore installations.

There is initially no response when salt builds on a blade's surface that has a protective oxide coating. However, once the gas turbine engine is running, damage processes

including thermal cycling, erosion, and others may occasionally lead to the mechanical rupture in the oxides layer on the blade's surface, which might lead to the destruction of the protecting layer. This quickens the oxidation process and causes the surface of turbine blade to corrode. Sometimes incomplete fuel combustion might result in the formation of a local decreasing environment. Such a decreasing environment may also harm the surface oxide layer, which serves as protection [69].

2.6.1 Hot Corrosion

Once high temp turbine blades constructed of super alloys are used in an atmosphere with sulfur and salt, hot corrosion may be a phenomenon that accelerates damage. The salt originates in the air or gets into the turbine through the fuel. Usually, the fuel is how sulfur reaches the turbine. The fundamental response that takes place is shown by:



The existence of vanadium, which forms V2O5 and, when combined with alkalis, may create low melting point (about 600 degree centigrade), which when melted, could aggressively dissolve metals oxides, can exacerbate hot corrosion of turbine blades. A famous corrosive agent, sodium sulphate, is created in the flame from sulfur-containing organic molecules, which may be found in practically any fuel, and sodium chloride or other sodium combinations [70]: Generally, the attack rate rises as the pollutant concentration does [71].

High temp hot corrosion (HTHC), also referred to as kind I, and low temp hot corrosion (LTHC), also called as kind II, are the two separate kinds of hot corrosion that were described. The formation of these two forms may be impacted by a several factors, including erosion processes, thermomechanical processes, temp and temp cycles, pollutant composition, velocity and gas composition, and alloy composition [72]. The sulfur produced as a result of the process is transformed into complicated unstable metal oxides, which spread deeper into the substrate and produce more sulfides [73]. An intergranular assault result from this.

2.6.2 High Temperature Hot Corrosion, Type I

High temp hot corrosion (HTHC) occurs in the 8000–9500-degree centigrade temp range. The interior chromium-rich sulfides of the elevated temp hot corrosion morphology are often followed by a porous, thick oxide layer on top of a chromium-depleted alloy matrix. The deposited molten sodium sulfate is often thought to be necessary for hot corrosion attacks to begin. A low rate of corrosion incubation time is resulted by a fastening corrosion assault is how type I hot corrosion often develops. The development of a protecting oxide scale is linked to the incubation duration. The disintegration of the protective oxide scale is thought to be responsible for the start of an accelerated corrosion assault [74].

Since the sulfur-rich gas entrained pollutant hits this area first, the highly pressurized side of the blade seems to be a suitable site for the commencement of the kind I reaction [73]. Other investigations indicated that most HTHC occurs distant from the blade's edges of gas turbine (for example, airfoil middle). The degree of this sort of rusting grew as one rose higher from the platform [64].

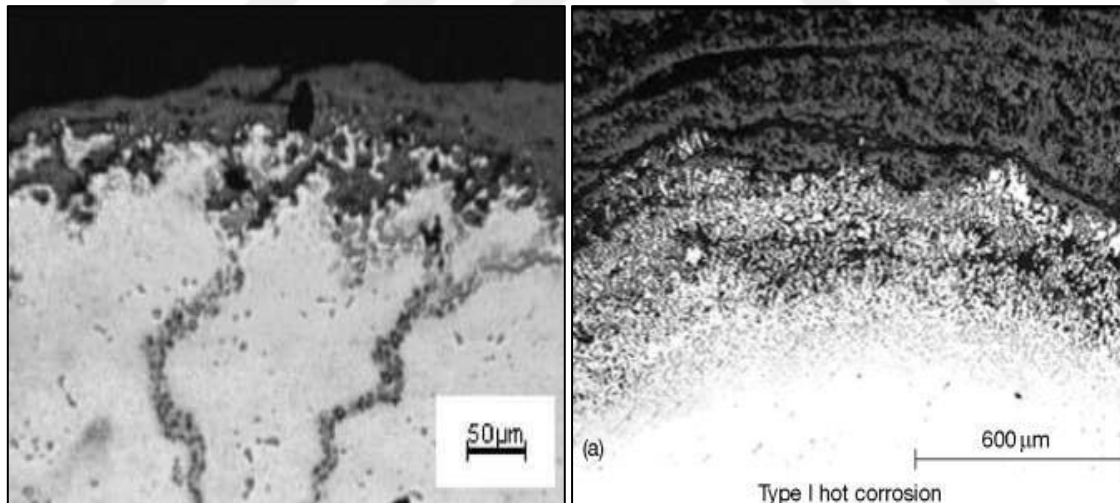


Figure 2.4: The Observation of Kind I Subscale Sulfide Particles, Grain Boundary Diffusion, and Hot Corrosion has Been Made.

2.6.3 Low Temperature Hot Corrosion, Type II

In the middle of the 1970s, low temp hot corrosion (LTHC) has been identified as a distinct mechanism of corrosion damage. It occurs at temps between 700 degree centigrade and 800 degree centigrade and calls for a sizable partial SO_3 pressure. The amount of combined salt that is present that is stabilized by a high SO_3 pressure, determines the severity of the assault. At low temps, large rates of corrosion may be seen as the equilibrium $\text{Pso}_3/\text{Pso}_2$ proportion rises with reducing temp. Especially for gas turbine components working in a maritime environment, significantly higher rates of attack displaying the pitting morphology were recorded [75]. Hot corrosion at low temperatures often exhibits little to no inter-granular attack. At low temps, LTHC (kind II) is more aggressive. Since the turbine blade platform seems to be a lower temp zone than the other sections, these turbine blade regions may be vulnerable to kind II hot corrosion attack [76]. According to reports, LTHC mostly affected the trailing and leading edge areas. The degree of this kind of corrosion reduced as distance from the platform increased [77]. Kind I was often visible in the areas close to the blade tip (Figure 3.4). Kind II dominated in the vicinity of the platform (Figure 3.5). Aero-engines seldom experience Kind II hot corrosion since the blades are often operated at greater temps. Low-temp Kind II hot corrosion may occur in industrial and marine gas turbines, nevertheless they run at lower temps. Adding more chromium to coatings or alloys increased the resistant to materials for Kind I and Kind II hot corrosion attacks.

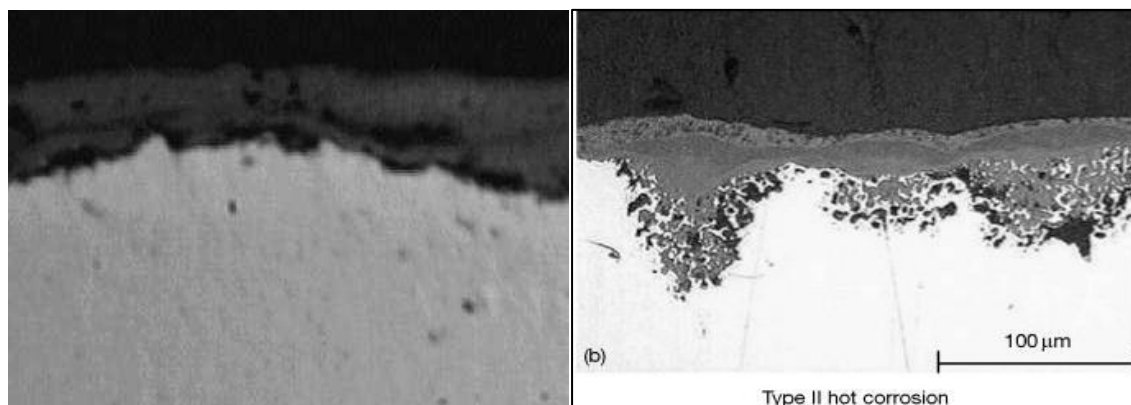


Figure 2.5: A kind II Hot Corrosion is Observed, Characterized by the Absence of Grain-Border Diffusion and The Presence of Sub-Scale Sulfide Particles [78].

At high temps, any of these corrosion kinds might easily attacks the nickel-based alloys used to make turbine blades. Corrosion results in material loss and may weaken a gas turbine blade component to the point where it collapses under normal stress. By carefully choosing materials, applying the right coatings, and maintaining the surface finish during whole course of the engine's lifetime, corrosion may be prevented. It was mentioned that appropriate coatings should be used to shield the blade material from corrosion [79]. To ensure resistance to corrosion, turbine blades are typically covered with complex coatings that are typically depending on aluminum and chromium, but frequently incorporate exotic elements like yttrium and platinum group metals. Attack is unavoidable when the engine is run in a appropriately polluted environment, either due to air pollution or the existence of too many dangerous components in the fuel. Typically, corrosion is simple to identify throughout normal inspection. Small corrosion pits that function as stress raisers and cause an early HCF or LCF failure are exceedingly difficult to find [80].

2.6.4 Failure Of Turbine Blade Due To Hot Corrosion- A Case Study

According to one case study, heated corrosion caused the blades of turbine constructed of nickel base super alloys, utilized throughout industrial gas turbines with a 150 MW capacity, to fail. The blade has been started 110 times over 5000 hrs of operation before being tripped on a severe vibration. The blade of turbine became weaker because of the uncoated blade material losing material because of heat corrosion. A research on hot gas route deposit reveals the existence of salt and that its amount levels have been adequate to promote hot corrosion at 0.1 mg/cm² [81].

2.7 EROSION FAILURE

By impinging on flow surfaces, hard particles remove material from the flow route in an abrasive manner. For erosion by impact to occur, these particles generally need to be bigger than 20 μm in diameter. Although this process seldom results in a catastrophic turbine blade's failure, it can contribute to other failure modes and may have a significant economic impact [82]. Erosion may happen to the turbine blades and compressor of a gas turbine. This is arguably more of an issue for aircraft engine

applications since most of the bigger particles are normally removed by state-of-the-art filtering systems utilized in industrial fields. Large foreign items impacting the blade's surface material in a gas turbine engine commonly cause damage to the blade's surface. These particles might flow into the engine by the intake air, the gas compressor through the gas stream, or they might be the consequence of engine parts that have broken off [83]. A rare kind of mechanical damage brought on by carbon particles is erosion. Once the nozzle spray pattern becomes compromised while passing through the turbine, these particles have been deposited as coke surrounding the fuel injection nozzles. Similar to this, ceramic thermal barriers coating particles that are placed to combustion chamber surfaces to help keep the walls cool separate owing to thermal stress and flow through the turbine's downstream blades, eroding the blades' surface [27].

Along with particle erosion, hot gas erosion seems to be another significant occurrence. Modern gas turbine blades that are air cooled function at metal temps that are lower than the temps of the gas route. By using a cooling air film or the natural boundary layer, the blades material surface was shielded. The blade surface asperities (roughness) that come into touch with the hot gas are exposed to severe thermal stress cycles if this cooling layer of air breaks down, even for brief periods of time, or if cooling efficacy declines. After a number of cycles, damage occurs, and as a result of increasing roughness (erosion), the issue becomes worse. Ultimately, this might result in lower performance and turbine blade failure [84].

2.7.1 Failure of Turbine Blade Due To Erosion- A Case Study

This instance involves a 150 MW gas turbine facility, and throughout the period of three years, the turbine was fired up 65 times and ran for around 1860 hrs. A short distance separates the plant from the ocean. These were found that a number of the moving and stationary blades have been harmed by solid items and particles that could have come from the first row's shattered blades. After closer examination, it was found that the moveable blades of the 1st-stage, which are situated upstream, had suffered extensive surface damage from foreign objects [85]. Figure 2.6 shows the 2nd turbine stage diaphragms of a gas turbine.

This demonstrates that there is extensive damage to the diaphragm blade surfaces due to foreign substances (solid particles). It was discovered that the materials that had been destroyed by the movable blades of the 1st-stage were what had damaged the blades of the later levels. Some of these blades may shatter early, harming later turbine gas Path blades, it is contended. The movable blades of the 1st-stage shattered first and damaged the blades of the succeeding stages, according to an analysis of the visual inspection's findings. The 1st-stage movable blades' breakdown into microscopic, fragile particles resulted in further damage. The turbine blades' surfaces were degraded on some of their surfaces as a result of that disintegration's stream of tiny foreign objects and solid particles [86].



Figure 2.6: Erosion of Gas Turbine Blade [87].

3. METHODOLOGY

3.1 THERMO – MECHANICAL FATIGUE

3.1.1 Creep

When a material is subjected to stress, a phenomenon known as creep deformation may occur in the material [88]. This could occur to any material. Once a particular piece of material is exposed to a specific level of stress over an extended period of time, the tension would produce strain spots on the metal, which will ultimately cause the piece to deform in a way that is irreversible. The application of stresses on metals that are less than their yield strength may cause the material to undergo creep deformation; the addition of heat speeds up this process [89].

The duration of exposure, the characteristics of the material, the amount of stress that is applied, as well as the temperature that the material is subjected to, all have a role in determining the pace at which the deformation takes place [90]. For instance, in the turbine section, a turbine blade that weighs 300 grams and rotates around at 10,000 RPM will experience a centrifugal force that is equivalent to 3 tons of force acting on it. When this force is combined with the fact that it is operating at 1400 degrees Celsius, there is always the possibility that the blade will fail due to creep [91]. When it comes to turbine blades, even the tiniest variation in their proportions might cause the rapidly moving blade to collide with the side walls of the turbine section. When a material approaches its melting point, it is more likely to creep, which is the most prevalent kind of deformation that may occur over a material that has been subjected to pressure for an extended period of time. Using the Kelvin or Rankine scale, the creep of any material may be identified at around 30 percent of the substance's melting point. This is a general statement [92]

This kind of deformation is the most significant for turbine blade manufacturers, and today's super alloys have been particularly created to counteract the effects of creep and to eradicate it totally at the working temperatures.

3.1.1.1 Microstructure analysis of creep

The creation of cavities and voids in the microstructure marks the beginning of the creep

deformation process, which may take many decades to complete. In the existence of a low stress, cavities would begin to develop on the grain boundaries that are aligned in the direction that the stress is coming from [93]. After these cavities have formed, further cavities would begin to form, and the existing cavities will continue to grow in size. The spread and expansion might be different from one another based on the kind of precipitate that is in between the grains and the allowance that it has [94]. Since the stress is constantly being applied to the material, the holes will ultimately become larger and spread into fractures along the grain boundaries, which will finally lead to creep failure. Both grains and grain borders run the danger of obtaining cavities when subjected to high levels of stress. Cavities may be generated via a process known as plastic expansion inside the grain as well as by grain boundary sliding. Both of these processes can take place [94].

It is exceedingly difficult to foresee an oncoming failure due to creep development because of the size of the first cavities, which vary from 0.1 microns to 10 microns. This is because there are no NDT tests available for use, and the size of the cavities. The phenomenon known as metallographic replication may be used to identify surface fatigue [92].

3.1.1.2 Nickel based super alloys

This is by far the most well-known and frequently utilized material in the production of turbine blades. Nickel seems to be the parent metal that is used to build a material that, after having additional alloys added to it, is able to withstand temperatures more than one thousand degrees Celsius without exhibiting any evidence of deformation. The microstructure of the metal is intended to overcome the process of creep deformation at any given temperature because of its strong creep resistance. This is made possible owing to the fact that the metal has a uniform temperature throughout. Among the super alloy family, microstructures that are constructed using a single crystal offer the greatest creep resistance [92].

3.1.2 Corrosion

During the process of the combustion phase, the exhaust gas that is produced combines with sodium chloride at extreme temps to produce a by-product known as sodium sulfate. The fact that this material is then deposited on the nozzle guiding vanes and rotary turbines

indicates that these components are being subjected to an oxidation assault [95]. Owing to the impurities interacting with the alloy, corrosive material such as these sediments will shorten the operating life of the turbine blades. This is because the alloy will become weaker as a result of the reaction [96].

3.1.2.1 Hot corrosion

Due to the active quantity of salts, such as sodium chloride and sodium sulfate, this kind of corrosion may be called an accelerated state corrosion. These salts mix to produce deposits on the blades, which damages the oxide layer that is on the surface [81].

Hot corrosion exhibits the following properties: There are two primary varieties of hot corrosion, designated kinds 1 and 2. The manner in which these different forms of corrosion develop and the amount of time it takes might well be altered by a number of different affecting aspects [92].

a. Kind 1 – High temp hot corrosion

This particular kind of corrosion takes place at temperatures ranging from 850 to 950 degrees Celsius. It begins with the disintegration of alkaline metal salt that is present on the turbine blade's surface, and then it gradually eats its way through the blade as it rises in temp [97]. At the beginning, the corrosive substance eats away at the oxide layer that is on the blade. After that, it removes the chromium from the alloy, which ultimately leads to the production of porous scaling on the blade. Sodium sulfate is the active salt in the sort of attack [81]. This form of salt may be present in the air streams over open seas; hence, airplanes traveling over huge water bodies might develop corrosion in the blades if thorough inspection is not performed. There are traces of vanadium present in some grades of fuel that are used in aircrafts, and if this deposit were to get onto the turbine blades, it would cause the blades to be destroyed [98]. The potential exists for this pollutant to occur at temperatures lower than 535 degrees Celsius.

The development of the response, from its beginning all the way until its conclusion, is as follows [99]:

- a. Phase 1: A limited breakdown of the oxide layer results in modest growth and a faint roughening of the region, but the blade does not lose its integrity or its chromium content at this point.

- b. Phase 2: The structure is stable, but the surface is becoming more noticeable since the oxide layer and the chromium are both being consumed by the reaction. This phase is also known as the oxidation phase.
- c. Phase 3: The oxide layer around the damaged region and the chromium from the area are both totally gone. The corrosion has spread deep into the blade, and after it is tested, the blade would be removed and found to be worthless.
- d. Phase 4: At this point, the reaction has spread across the whole blade, and it is clear that structural components are being eroded away.
- e. Kind 2 - low temp hot corrosion

This form of corrosion is active between 650 and 800 degrees Celsius, and its primary characteristics include pitting and moderate interactions with compounds that have low melting temperatures, such as cobalt sulphate [92].

3.1.3 Foreign Object Damage

This kind of damage results from the swallowing of foreign debris or even components that are part of the jet engine itself, as the name indicates. This debris may have a significant impact on the engine performance as well as its structural integrity, as the components of the engine, such as the turbine blade, travel at extremely high speeds [100]. Any kind of contact with an item, no matter how little, might jeopardize the structural blade's performance. The point of impact between the debris and the damaged blades is shown by a series of minute scratches along the structure's tips and edges. If this is not examined and changed, it will cause fractures that will spread throughout the blade, which will ultimately result in the blade breaking in a disastrous way [101]. References in the field of technology for Damage caused by foreign objects is typically associated with the stages that come before the combustion chamber. Debris cannot reach the turbine blades due to their size, and the only particles that could cause damage to the turbine blades are those that are both durable and small enough to make it through the first three sections. Extreme scoring and damage might be caused on the turbine blades by sand, dust, bits of metal, and even ash from volcanic eruptions [102].

3.2 COATING THE BLADE

3.2.1 Coatings

The coating on turbine blades is utilized to give an additional layer of protection vs the heating and corrosive elements that are present in the turbine section. A coating is a specific layer of material that is put on a surface in order to avoid the surface from becoming damaged [103].

3.2.1.1 Thermal barrier coating (TBC)

The typical working temperatures of a turbine blade have increased to 1000 degrees Celsius, and with the assistance of ceramic thermal barrier coatings and the cooling mechanism, this temperature has been increased to 1400 degrees Celsius. The blade is protected against rust and corrosion thanks to the ultrathin layer of coating that was applied to it, which also enables it to function normally at the elevated temps. Ceramic is a naturally occurring insulator, and as such, it finds widespread use in settings that call for protection versus heat and the presence of the need for thermal barriers. The coating is applied so that it will be able to withstand attacks from the stress of unloading and loading forces and exhaust gases and fine particle debris from combustion for a predetermined number of cycles or service life time period. Within this time period, the coating should be able to withstand these types of attacks. In addition to this, this must maintain its neutrality and not react with or weaken the metal to which the coating is being put [104], [105].

Before applying the protective coating, there are three procedures that need to be completed in order to ensure that it is applied correctly. These processes are as follows [106]:

- a. The first thing that is done is to treat the blade's surface with a chemical thermal treatment, and this treatment either comprises aluminum or a blend of materials that includes aluminum as the basis along with elements such silicon and yttrium. As a result of the reaction that takes place between the aluminum and the surface of the alloy after this treatment, a coating is produced on the blade.
- b. Thereafter, a top coat of evaporated alloys is applied to the blade by utilizing a vacuum to evaporate and afterwards condensing all of the components in an equal distribution on the blade.

- c. The arc plasma spraying method is used to create the coating utilizing powder as the material, which is the last phase.

3.3 FINITE ELEMENT ANALYSIS

In the fields of engineering and science, finite element analysis is a technique that may solve specific issues, often on an approximatively level. Its primary use is in addressing issues for which there is not an accurate answer that can be articulated in some kind of mathematics [107]. As a consequence of this, the approach in question is a numerical one rather than an analytical one. Techniques of this kind are required because analytical approaches are unable to handle the actual and complex issues that are encountered in engineering [108]. This is why these methods are required. For instance, engineering strength of materials or the mathematical theory of elasticity can be used to perform an analytical calculation of the stresses and strains in a bent beam. However, neither of these approaches will be very helpful in determining what is going on in a portion of a car's suspension system when the vehicle is cornering.

Finding the stresses and strains that occur in engineering components when they are subjected to load was one of the very first applications of finite element analysis (FEA). When applied to any realistic model of an engineering component, FEA necessitates an enormous amount of computation, and the development of the method has been dependent on the availability of suitable digital computers for it to run on. FEA is used to analyze the behavior of engineering components under a variety of different conditions. The method is now applied to problems involving a wide variety of phenomena, such as vibrations, heat conduction, fluid mechanics, and electrostatics, as well as a wide variety of material properties, such as linear-elastic (Hookean) behavior and behavior involving deviation from Hooke's law. In addition, the method is now applied to problems involving a wide variety of material properties, such as the behavior of linear-elastic (Hookean) systems (for example, plasticity or rubber-elasticity).

There are currently a large number of all-inclusive general-purpose computer packages available on the market that are able to deal with a diverse range of phenomena, in addition to more specialized computer packages designed for specific applications, such as the investigation of dynamic phenomena or large-scale plastic flow. These kinds of programs can be executed on anything from a microcomputer to a supercomputer, depending on the

nature of the data being analyzed and the level of complexity involved. The FEA procedure is typically carried out in stages. It is possible to use it to solve issues with a single dimension, but in most situations, there is an area or volume in which the answer must be found. This is then broken down into a number of more manageable regions or volumes, which are referred to as finite elements. The discretization process is shown in figure 1, which depicts a two-dimensional model of a spanner that was thus split. The technique is referred to as a mesh, and the assembly of parts is termed a discretization.

3.4 STRUCTURAL ANALYSIS

ANSYS Autodyn is a computer simulation program that can simulate the reaction of materials under short-term severe loadings such as impacts, explosions, or high pressure.

3.4.1 ANSYS Mechanical

ANSYS Mechanical seems to be a tool for doing finite element analysis, which may be used for structural analysis, as well as dynamic, nonlinear, and linear investigations. This computer simulation program offers finite elements to model behavior, as well as support for material models and equation solvers. It may be used to address a broad variety of challenges pertaining to mechanical design. ANSYS Mechanical is equipped with coupled-physics capabilities and thermal analysis capabilities as well. These capabilities involve thermo-electric, thermal–structural, piezoelectric, and acoustics analysis.

3.4.2 Fluid Dynamics

FENSAP-ICE, CFX, and CFD in addition to ANSYS Computational Fluid Dynamics software tools are software applications that engineers use for design and analysis. These tools are connected to Fluent. These tools are able to simulate the flow of fluids in a virtual environment. For instance, they can simulate the fluid dynamics of ship hulls; the aerodynamics of aircraft; gas turbine engines (including the compressors, combustion chamber, turbines, and afterburners); pumps, fans, HVAC systems, mixing vessels, hydro cyclones, and vacuum cleaners, among other things.

Constructing the mesh is an essential step before the FEA solution can be mathematically solved. A node may be found at the corner of each element that makes up the mesh. These little bits are referred to as elements. The property specification will determine the kind of mesh that is used.

Control over the element size, element order, and local refinement are provided through a variety of options that may be applied. Since the accuracy of the solution is so dependent on the fidelity of the mesh, it is essential to take the time to define a high-quality mesh for your simulations. This is because the accuracy of the solution is so dependent on the fidelity of the mesh.

3.5 THE IMPORTANCE OF THE MESH ON CONVERGENCE

In most cases, a larger number of elements results in better accuracy for the answer. This is because there are more nodes accessible for the calculation of the response, as well as the fact that smaller elements lessen mistakes caused by discretization. The point at which a mesh-independent solution becomes possible represents the practical threshold for the impact of the mesh on solution precision. This implies that the solution remains invariant, irrespective of subsequent decreases in the size of the element.

The implementation of mesh control techniques facilitates convergence by both globally and locally decreasing the element size and monitoring the resultant changes in outcomes. It has been observed that the convergence of models can be achieved with a reduced number of second-order elements, such as Parabolic Tetrahedrons, as compared to linear elements. The rationale behind this assertion is that a second-order element possesses the ability to capture a strain field that is more intricate than that which can be captured by a linear element. The computational expense of second-order elements is generally higher because of the increased number of nodes, resulting in longer solution times.

The present analysis showcases the impact of mesh refinement on the von Mises stress at a localized region of stress concentration. A decrease in stress variation at the area of interest is observed as the mesh evolves from Mesh 1 to Mesh 3. The aforementioned statement implies that the mesh with a higher degree of fineness approaches a state of solution that is

independent of the mesh, resulting in minimal alterations in the solution as the mesh undergoes further refinement:

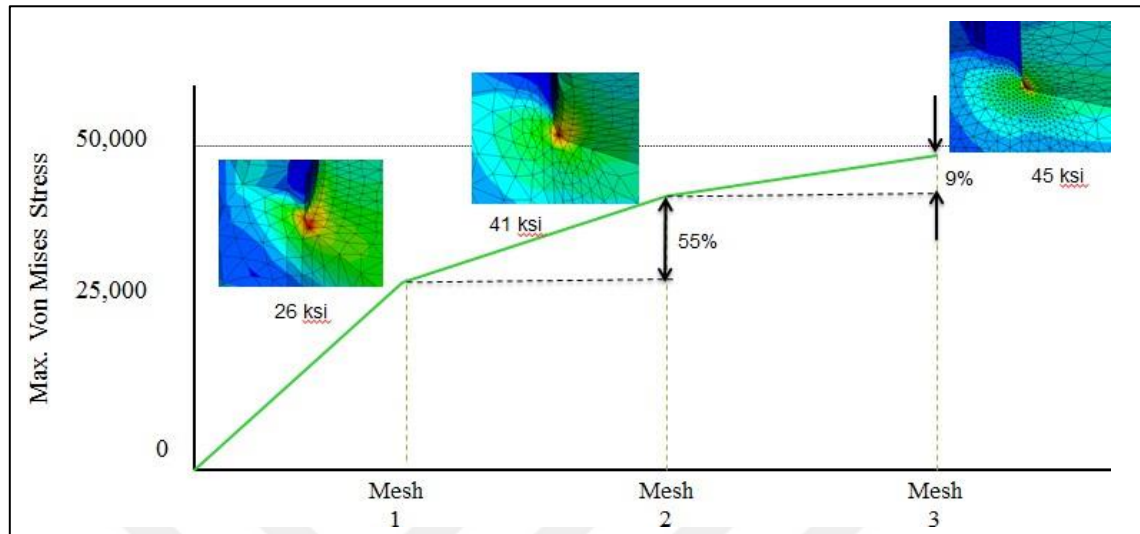


Figure 3.1: Mesh Convergence.

3.6 CFD SIMULATIONS

The resolution of issues pertaining to fluid dynamics has historically been approached using both analytical and experimental means. In recent years, due to a constant evolution of computers, computational fluid dynamics (CFD) modeling has grown into one of the three fundamental approaches used to solve problems involving fluid dynamics and heat exchange [109]. The other two approaches are finite element modeling and experimental testing. While many people still use the analytical technique, and tests are being carried out, the trend in industrial design is toward a larger usage of the computational approach. This is despite the fact that many people still use the analytical method [110]. This is because CFD has some special qualities that make it a quick approach that is also accurate, and this is the reason why this is the case. In particular, it is feasible to have: an approximate solution to the formulas that control complicated fluid flows; a more cost-effective technique; both of these things at the same time.

- a. Create a simulation of situations that cannot be replicated in the actual experiments.
- b. It should provide information that is thorough, visible, and complete on the flow.

Because of all of these benefits, CFD is presently utilized in a wide variety of research and industrial domains, including those of aerospace, automotive, biomedical, power, and a great several others [111]. At the beginning phases of the development of CFD methodologies, users were forced to construct programs in order to successfully solve the issue. Later on, when there was a greater interest from companies and academics, commercial softwares were produced. These softwares enable the user to bypass the challenges of coding, which substantially accelerates the process of finding solutions to problems involving fluid dynamics. ESI Group CFD-ACE, Flow Science FLOW-3D, Comsol, Ansys Fluent, and Ansys CFX are among the commercial software programs that are used most often in the modern day.

It is so crucial to employ CFD for the investigation of turbulent flows, as well as what the current computing limitations are. In conclusion, the process of creating a CFD simulation would be discussed briefly, with a focus on providing further information on one of the most important processes, which is the development of the mesh [112].

3.6.1 Turbulence

People are constantly exposed to turbulent flows, which are characterized by a flow of a fluid that is non-stationary, irregular, and chaotic. This is something that individuals face on a daily basis. A few instances of this are the movement of smoke from a cigarette in an upward direction, the blending of milk and coffee inside of a cup, and the uneven wake of a river downstream from a bridge pylon. While the idea of turbulence is straightforward, the influence that turbulence has on the overall properties of a flow is not as straightforward [113].

While studying a turbulent flow, one may quickly see complex rotating structures that are characteristic of this regime of movement and go by the term turbulent eddies. These structures indicate a feature of this movement regime. In particular, they manifest themselves when the flow is distinguished by a high Reynolds' number. Large-scale vortex formations may be seen on a variety of time and space scales, where they interact and trade energy with one another. The greatest amount of the flow's kinetic energy is contained at the biggest scale. When bigger buildings are dismantled and smaller ones are built in their place, this energy would progressively migrate to more manageable sizes.

3.6.2 General Fluid Flow and Heat Transfer Equations

The Navier-Stokes formulas, also known as the momentum formulas, and the First Law of Thermodynamics, often known as the energy formula, are the formulas that determine how fluids move and how heat is transferred. The PDES that governs the situation may be expressed as [114]:

3.6.2.1 Continuity formula:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad (3.1)$$

3.6.2.2 X-Momentum formula:

$$\begin{aligned} & \rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \rho w \frac{\partial u}{\partial z} \\ &= \rho g_x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} [2\mu \frac{\partial u}{\partial x}] + \frac{\partial}{\partial y} [\mu (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})] + \frac{\partial}{\partial z} [\mu (\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x})] \\ & \quad + S_\omega + S_{DR} \end{aligned} \quad (3.2)$$

3.6.2.3 Y-Momentum formula:

$$\begin{aligned} & \rho \frac{\partial v}{\partial t} + \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} + \rho w \frac{\partial v}{\partial z} \\ &= \rho g_y - \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} [\mu (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})] + \frac{\partial}{\partial y} [2\mu \frac{\partial v}{\partial y}] + \frac{\partial}{\partial z} [\mu (\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y})] \\ & \quad + S_\omega + S_{DR} \end{aligned} \quad (3.3)$$

3.6.2.4 Z-Momentum formula:

$$\begin{aligned}
& \rho \frac{\partial w}{\partial t} + \rho u \frac{\partial w}{\partial x} + \rho v \frac{\partial w}{\partial y} + \rho w \frac{\partial w}{\partial z} \\
& = \rho g_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left[\mu \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[2\mu \frac{\partial w}{\partial z} \right] \\
& \quad + S_\omega + S_{DR}
\end{aligned} \tag{3.4}$$

In the formulas for momentum, the two source terms, one for rotating coordinates and the other for dispersed resistances, respectively, may be found. For purposes of generalization, the phrase distributed resistance may be expressed as [115]:

$$S_{DR} = - \left(K_i + \frac{f}{D_H} \right) \frac{\rho V_i^2}{2} - C\mu V_i \tag{3.5}$$

where i is the direction of the global coordinate system (the u, v, and w momentum formula), and the other components have been defined in the section before this one. It is important to keep in mind that the K-factor term could only work on one momentum formula at a time since the K-factor for each direction is completely unique. The behavior of the other two forms of resistance is same across all momentum equations. The other phrase used to describe the source is revolving flow [116]. This concept may also be expressed in generic form as:

$$S_\omega = -2\rho\omega_i \times V_i - \rho\omega_i \times \omega_i \times r_i \tag{3.6}$$

where i denotes the direction of the global coordinate system, ω_i denotes the rotational speed, and r indicates the distance from the rotational axis. The energy formula is expressed in terms of the static temp when it applies to incompressible and subsonic compressible flow:

$$\begin{aligned}
& \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \frac{\partial T}{\partial x} + \rho C_p v \frac{\partial T}{\partial y} + \rho C_p w \frac{\partial T}{\partial z} \\
& = \frac{\partial}{\partial x} \left[k \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[k \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[k \frac{\partial T}{\partial z} \right] + q_v
\end{aligned} \tag{3.7}$$

Once applied to multi-phase fluxes, such as those including water and steam, the energy formula is expressed in terms of enthalpy rather than kinetic energy:

$$\rho \frac{\partial h}{\partial t} + \rho u \frac{\partial h}{\partial x} + \rho v \frac{\partial h}{\partial y} + \rho w \frac{\partial h}{\partial z} = \frac{\partial}{\partial x} \left[k \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[k \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[k \frac{\partial T}{\partial z} \right] + q_v \tag{3.8}$$

Until the release of CFD design Version 9.0, the computations for humidity were performed utilizing a formulation that was dependent on enthalpy. The enthalpy of the fluid in this case denotes the combined energy of the moisture, whether in its gaseous or liquid state, and that of the air or carrier gas [117]. However, subsequent iterations have utilized a temperature-dependent approach for moist gas flow, coupled with a distinct methodology for incorporating the phase transition in the specific heat. This was done to accurately forecast the behavior of the system. When it comes to steam and water fluxes, the enthalpy represents the total energy amount present in both the liquid and vapor phases. The energy formula is stated in terms of the total temp when it is applied to compressible flow [118]:

$$\begin{aligned} \rho C_p \left(\frac{\partial T_0}{\partial t} \right) + \rho C_p V_i \left(\frac{\partial T_0}{\partial X_i} \right) = \frac{\partial}{\partial X_i} \left[k \frac{\partial T_0}{\partial X_i} \right] + qv \\ + \mu V_i \left[\frac{\partial V_i}{\partial X_j} \frac{\partial V_j}{\partial X_j} + \frac{\partial}{\partial X_i} \frac{\partial V_j}{\partial X_j} \right] + \frac{1}{2C_p} \frac{\partial}{\partial X_j} \left[k \frac{\partial}{\partial X_j} (V_j V_j) \right] + \Phi \end{aligned} \quad (3.9)$$

When Φ the dissipation function, denoted by, is used. Please take note that, for the sake of brevity, the formula for total energy uses the Einstein tensor notation. The latter three phrases are only applicable to flows that are compressible.

C_p : constant pressure specific heating, g_x, g_y, g_z : gravitational acceleration in x, y, z directions, h : enthalpy, qV : volumetric heating source, u : x-axis velocity, v : y-axis velocity, w : z-axis velocity

The continuity, momentum, and energy formulas each express 3.9 formulas in their respective 3.9 variables: u, v, w, p, T or T_0 . They provide a description of the fluid flow and heating transfer that occurs under circumstances of steady state for geometries that are Cartesian. In steady-state circumstances and axisymmetric geometries, the swirl velocity component is considered (out-of-plane component).

3.6.2.5 Continuity formula:

$$\frac{\partial}{\partial r} (r \rho u_r) + \frac{\partial}{\partial z} (r \rho v_z) = 0 \quad (3.10)$$

3.6.2.6 R-Momentum formula:

$$= -\frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} [r\mu \frac{\partial u_r}{\partial r}] + \frac{\partial}{\partial z} [\mu \frac{\partial u_r}{\partial z}] + \frac{\partial}{\partial z} [\mu \frac{\partial v_z}{\partial r}] - \frac{2\mu v_r}{r^2} + S_\omega + S_{DR} \quad (3.11)$$

3.6.2.7 Z-Momentum formula:

$$= -\frac{\partial p}{\partial z} + \rho g_z + \frac{1}{r} \frac{\partial}{\partial r} [r\mu \frac{\partial v_z}{\partial r}] + \frac{\partial}{\partial z} [\mu \frac{\partial v_z}{\partial z}] + \frac{1}{r} \frac{\partial}{\partial r} [r\mu \frac{\partial u_r}{\partial z}] + \frac{\partial}{\partial z} [\mu \frac{\partial v_z}{\partial z}] + S_{DR} \quad (3.12)$$

3.6.2.8 Swirl-Velocity formula:

$$\frac{\partial w_\theta}{\partial r} + \rho v_z \frac{\partial w_\theta}{\partial z} + \frac{\rho u_r}{r} \frac{w_\theta}{r} = \frac{1}{r} \frac{\partial}{\partial r} [r\mu \frac{\partial w_\theta}{\partial r}] + \frac{\partial}{\partial z} [\mu \frac{\partial w_\theta}{\partial z}] - \frac{w_\theta}{r} \frac{\partial \mu}{\partial r} - \frac{\mu w_\theta}{r} + S_{DR} + S_\omega \quad (3.13)$$

There are no extra terms for axisymmetric flows in the formulas governing energy.

3.6.3 Concept of Computational Fluid Dynamics

The fluids engineering systems simulation via the use of modeling (mathematical physical formulation problems) and numerical techniques is referred to as Computational Fluid Dynamics, or CFD for short (grid generations, numerical parameters, solvers, and, discretization methods etc.) [119]. The procedure may be shown in figure 3.6.

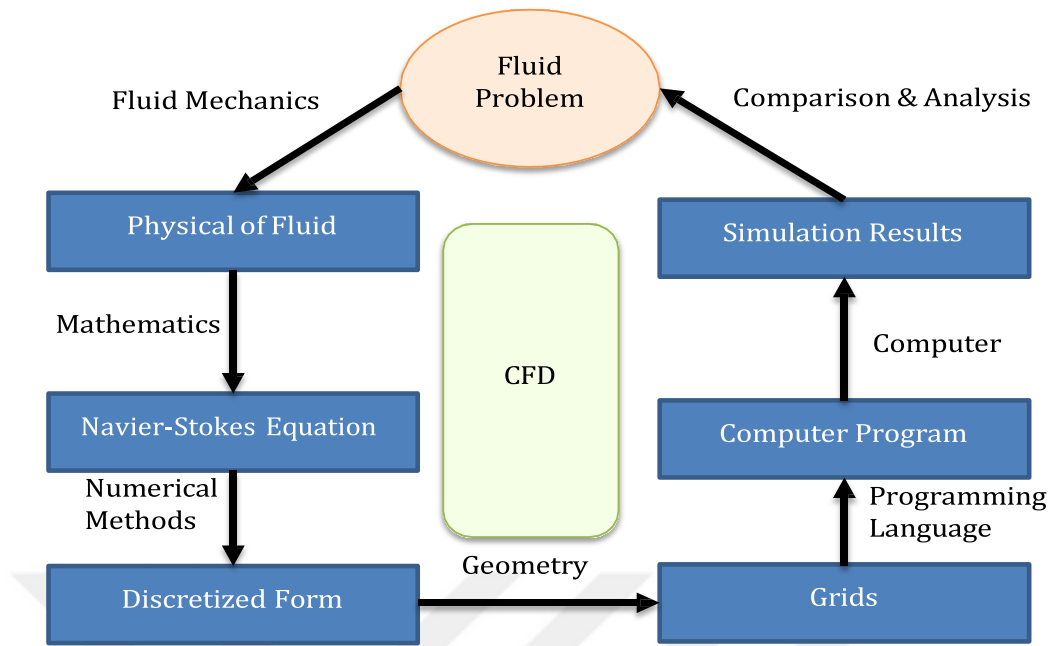


Figure 3.2: Process of Computational Fluid Dynamics [120].

To begin, there is an issue with the fluid. In order to find a solution to this issue, it need to be familiar with the fluid's physical characteristics and use the theory of fluid mechanics. After that, it will be able to explain these physical qualities using mathematical formulas. This is known as the Navier-Stokes Formula, and it is the equation that is used to control CFD. Since it is an analytical formula, the Navier-Stokes Equation can be comprehended by humans and its solutions may be worked out on paper. Although, in order for us to use the computer to solve this equation, it will need to convert it to the discretized form first. The techniques of numerical discretization, including finite difference, finite element, and finite volume approaches, are the ones serving as the translators. As a consequence of this, it also need to break up the whole of the problem domain it are working on into a large number of smaller portions since our discretization relies on them. After that, it will be able to develop programs to solve the problems. Fortran and C are the most common programming languages. Workstations or supercomputers are often used in the execution of the applications. In the very end, it will be able to get the outcomes of our simulation. The findings of the simulation may be analyzed and compared with those of the experiments and the actual issue. In the event that the findings are not enough to address the issue, it will need to continue the procedure until discovered a solution that satisfies

everyone.

3.7 IMPORTANCE OF COMPUTATIONAL FLUID DYNAMICS

The investigation of fluids may be approached from three different angles: theoretical analysis, hands-on experimentation, and computer modeling (CFD). In comparison to traditional experimentation, the benefits of using CFD as a novel approach are several.

3.7.1 Application of Computational Fluid Dynamics

3.7.1.1 Physics of fluid

Fluid includes gas and liquid take, for instance, air and water. Fluid has a variety of essential characteristics, including its viscosity, density, temp, pressure, and velocity. The mass of a fluid expressed as a percentage of its volume is referred to as its density (3.14). If a fluid's density never changes—or only does so by a little amount—we refer to that fluid as being an incompressible fluid. If there is a change in the density of a fluid over time, we refer to that fluid as a compressible fluid. In a normal situation, we are able to treat air and water as if they were incompressible fluids. Once the fluid becomes incompressible, then the formulas that we use to model this sort of fluid may be simplified.

$$\rho = \frac{M}{V} \left[\frac{kg}{m^3} \right] \quad (3.14)$$

A fluid's viscosity equation (3.15), an intrinsic feature that determines the amount of resistance it presents to motion, is measured in centipoise. For instance, stirring honey is considerably more difficult than stirring water because honey has a lot higher viscosity than water. Water, on the other hand, has a much lower viscosity than honey.

$$\mu = \left[\frac{Ns}{m^2} \right] = [\text{Posie}] \quad (3.15)$$

Table 3.1 : The Viscosities and Densities of Honey, Water And Air.

Substance	Air (18 degree centigrade)	Water (20 degree centigrade)	Honey (20°C)
Density (kg/m ³)	1.275	1000	1446
Viscosity (ρ)	1.82×10^{-2}	1.002×10^{-2}	190

3.8 NAVIER-STOKES EQUATIONS

3.8.1 Conservation Law

In the field of computational fluid dynamics, the formulas of Navier-Stokes are the governing formulas. It is predicated on the principle of the conservation of the fluid's physical characteristics. The amount of change that occurs in an item's attributes, such as its momentum, energy, and mass, is determined by the amount of output and input that the object receives, according to the concept of conservational law. Take, for instance, the following illustration of the change in mass shown by the object:

$$\frac{dM}{dt} = \dot{m}_{in} - \dot{m}_{out} \quad (3.16)$$

If $\dot{m}_{in} - \dot{m}_{out} = 0$, we have

$$\frac{dM}{dt} = 0 \quad (3.17)$$

Which means

$$M = \text{const} \quad (3.18)$$

3.9 FINITE VOLUME METHOD

The finite volume technique, often known as the FVM, is a technique for rewriting partial differential formulas as algebraic formulas to describe them and perform evaluations on them. [1] The application of the divergence theorem is a common technique in the finite volume methodology, whereby volume integrals within a partial differential equation

containing a divergence component are converted into surface integrals. The discrete volume method, commonly referred to as the finite volume technique, is a numerical approach used in computational fluid dynamics and other related fields. Subsequently, the fluxes situated at the surfaces of every finite volume are computed by utilizing the terms subsequent to their evaluation. The methodologies are deemed conservative as the amount of flux that infiltrates a given volume is equivalent to the amount of flux that departs from the adjacent volume. The fact that the finite volume approach may be simply designed to accommodate unstructured meshes is another benefit of using this technique. Many different computational fluid dynamics software programs make use of this approach. In a mesh, the term "finite volume" refers to the relatively limited volume that surrounds each node point. [2]

It is possible to draw comparisons and contrasts among the finite volume techniques, finite differences approaches, and finite element techniques. Finite variance methods are utilized to approximate derivatives through the utilization of nodal values. On the other hand, finite element approaches generate local predictions of a solution by utilizing local data. Finally, finite element methods are used to construct a global prediction by piecing together the local projections [121], [122]. An approach known as the finite volume technique, on the other hand, employs precise equations to determine the mean value of the solution across certain volume. It then makes use of this information to create estimates of the solution inside individual cells. The Navier-Stokes equations may be classified as analytical equations. The problems in question possess a level of comprehensibility that is accessible to human cognition and can be resolved by human agents. However, to achieve resolution via computational means, it is necessary to first transform them into a discretized format. The method of discretization is presented herein. The three most prevalent discretization methods are the finite difference method, the technique using finite elements, and the finite volume approach. This section will expound on the finite volume methodology.

3.10 THE APPROACH OF FINITE VOLUME METHOD

The general conservation law issue might additionally be taken into consideration, as it is illustrated by the following.

$$\frac{\partial u}{\partial t} + \nabla \cdot f(u) = 0 \quad (3.19)$$

In this context, the variable "u" denotes a vector of states, while "f" denotes the corresponding flux tensor. The spatial domain may be partitioned into finite volumes or cells, as previously mentioned. When considering a specific cell, the volume integral is performed over the entire volume of said cell, yielding the result.

$$\int_{v_i} \frac{\partial u}{\partial t} dv + \int_{v_i} \nabla \cdot f(u) dv = 0 \quad (3.20)$$

Upon performing integration of the initial term to obtain the volume normal and subsequently applying the divergence theorem to the second term, the resulting outcome is obtained.

$$v_i \frac{du_i}{dt} + \oint_{S_i} f(u) \cdot n dS = 0 \quad (3.21)$$

where n is a unit vector perpendicular to the surface and pointing outward, and S_i is the entire area of the cell's surface. Finally, we may offer the overall result that corresponds to equation (8), which is.

$$\frac{du_i}{dt} + \frac{1}{v_i} \oint_{S_i} f(u) \cdot n dS = 0 \quad (3.22)$$

The magnitudes of the edge fluxes may be reconstructed through the process of extrapolation or interpolation of the cell the mean. The selection of the numerical scheme is contingent upon the geometry of the issue and the construction of the mesh. The MUSCL reconstruction technique is frequently employed in high-resolution schemes that encounter shocks or discontinuities within the solution. The Navier-Stokes formula's general form can be integrated over a volume of control and subsequently subjected to Gauss Theory.

$$\int_V \frac{\partial}{\partial x_i} \Phi dV = \int_S \Phi \cdot n_i dS \quad (3.23)$$

The integral form of the formula for Navier-Stokes can be obtained.

$$\int_V \frac{\partial(\rho\Phi)}{\partial t} dV + \int_S (\rho U_i \Phi - \Gamma \frac{\partial \Phi}{\partial x_i}) \cdot n_i dS = \int_V q_\Phi dV \quad (3.24)$$

One possible approach to estimate the volume integral involves computing the product of the volume of the controlling and the magnitude of the function at its centroid. As illustrated in Figure 3.3, the domain under consideration is two-dimensional. In order to estimate the momentum and mass of controlling volume P, it is necessary to employ an approximation method.

$$m = \int_{V_i} \rho dV \approx \rho_p V, mu = \int_{V_i} \rho_i u_i dV \approx \rho_p u_p V \quad (3.25)$$

To estimate the surface integral, such as the pressure force, one may utilize the following method:

$$\oint_{S_i} P dS \approx \sum_k P_k S_k k = n, s, e, w \quad (3.26)$$

Typically, parameters are stored at the center of the controlling volume. To obtain P_k , which is situated at the surface of the controlling volume, interpolation is necessary. There are generally two distinct forms of interpolation that are commonly utilized: central interpolation and upwind interpolation.

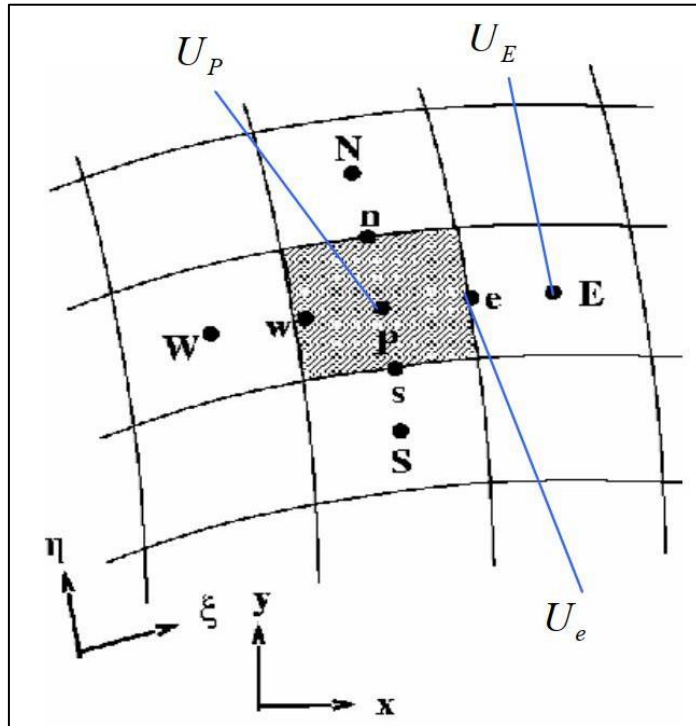


Figure 3.3: Two-Dimensional Grid Structured Domains.

Upwind Interpolation

$$U_e = \begin{cases} U_P & \text{if } (\vec{U} \cdot \vec{n})_e > 0 \\ U_E & \text{if } (\vec{U} \cdot \vec{n})_e < 0 \end{cases} \quad (3.27)$$

Central Interpolation

$$U_e = U_E \lambda_e + U_P (1 - \lambda_e) \lambda_e = \frac{x_e - x_P}{x_E - x_P} \quad (3.28)$$

3.11 CONSERVATION OF FINITE VOLUME METHOD

When employing the finite element and finite difference methodologies for discretizing the Navier-Stokes equation, it is necessary to manually regulate the preservation of energy, momentum, and mass. The technique of finite volumes enables the determination that the satisfaction of the Navier-Stokes formula in each control volume implies its satisfaction throughout the entire domain. Stated differently, when conservation is upheld within each individual control volume, it becomes inherently upheld throughout the entirety of the domain. Finite volume is the preferred method in computerized fluid dynamics due to this reason.

3.12 FLUID FLOW MODEL

The selection of a turbine blade airfoil for analysis was based on its high loading and low solidity, as well as the abundance of relevant test data available in existing literature. The initial airfoil for the turbine blade was employed by Daniels and Browne [123]. The airfoil exhibits discernible features. The object in question possesses a considerable thickness, a pronounced camber, and a dense composition, resulting in a diverse range of fluidic phenomena and a limited applicability of conventional methodologies.

3.12.1 Flow Governing Equations

3.12.2 Continuity Equation

The continuity formula is derived from the principle of mass conservation:

$$\frac{\partial(\rho V_x)}{\partial x} + \frac{\partial(\rho V_y)}{\partial y} = 0 \quad (3.29)$$

3.12.3 Momentum Equation

The system is in a state of force equilibrium in the x and y directions.

$$\frac{\partial(\rho V_x V_x)}{\partial x} + \frac{\partial(\rho V_y V_x)}{\partial y} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}(\mu_e \frac{\partial V_x}{\partial x}) + \frac{\partial}{\partial y}(\mu_e \frac{\partial V_x}{\partial y}) + T_x \quad (3.30)$$

$$\frac{\partial(\rho V_x V_y)}{\partial x} + \frac{\partial(\rho V_y V_y)}{\partial y} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}(\mu_e \frac{\partial V_y}{\partial x}) + \frac{\partial}{\partial y}(\mu_e \frac{\partial V_y}{\partial y}) + T_y \quad (3.31)$$

Where

$$T_x = \frac{\partial}{\partial x}(\mu \frac{\partial V_x}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial V_y}{\partial x}) \quad (3.32)$$

$$T_y = \frac{\partial}{\partial x}(\mu \frac{\partial V_x}{\partial y}) + \frac{\partial}{\partial y}(\mu \frac{\partial V_y}{\partial y}) \quad (3.33)$$

3.12.4 Energy Equation

The energy equation, which is stated in terms of the overall (stagnation) temp, is derived from the law of energy conservation:

$$\begin{aligned} \frac{\partial}{\partial x}(\rho v_x C_p T_0) + \frac{\partial}{\partial y}(\rho v_y C_p T_0) \\ = \frac{\partial}{\partial x}(k \frac{\partial T_0}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T_0}{\partial y}) + w^v + e^k + q_v + \Phi \end{aligned} \quad (3.34)$$

The formula utilized for the determination of static temp involves the utilization of the total temp:

$$T = T_0 + \frac{V^2}{2C_p} \quad (3.35)$$

The viscous work term is:

$$w^v = V_x \mu \left[\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial x^2} + \frac{\partial}{\partial x} \left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} \right) \right. \\ \left. + v_y \mu \left[\frac{\partial^2 V_y}{\partial x^2} + \frac{\partial^2 V_y}{\partial y^2} + \frac{\partial}{\partial y} \left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} \right) \right] \right] \quad (3.36)$$

The viscous dissipation term is:

$$\Phi = 2\mu \left[\left(\frac{\partial v_x}{\partial x} \right)^2 + \left(\frac{\partial v_y}{\partial y} \right)^2 \right] + \mu \left[\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} \right)^2 \right] \quad (3.37)$$

The kinetic energy term is:

$$e^k = -\frac{\sigma}{\partial x} \left[\frac{\kappa}{C_p} \frac{\sigma}{\partial x} \left(\frac{1}{2} |\mathbf{v}^2| \right) \right] - \frac{\sigma}{\partial y} \left[\frac{\kappa}{C_p} \frac{\sigma}{\partial y} \left(\frac{1}{2} |\mathbf{v}^2| \right) \right] \quad (3.38)$$

Turbine Blade and Cascade Geometry

The profile coordinates are listed in table (1) and the blade cascade geometry is illustrated in figure (3.4). The main cascade dimensions are summarized as follows:

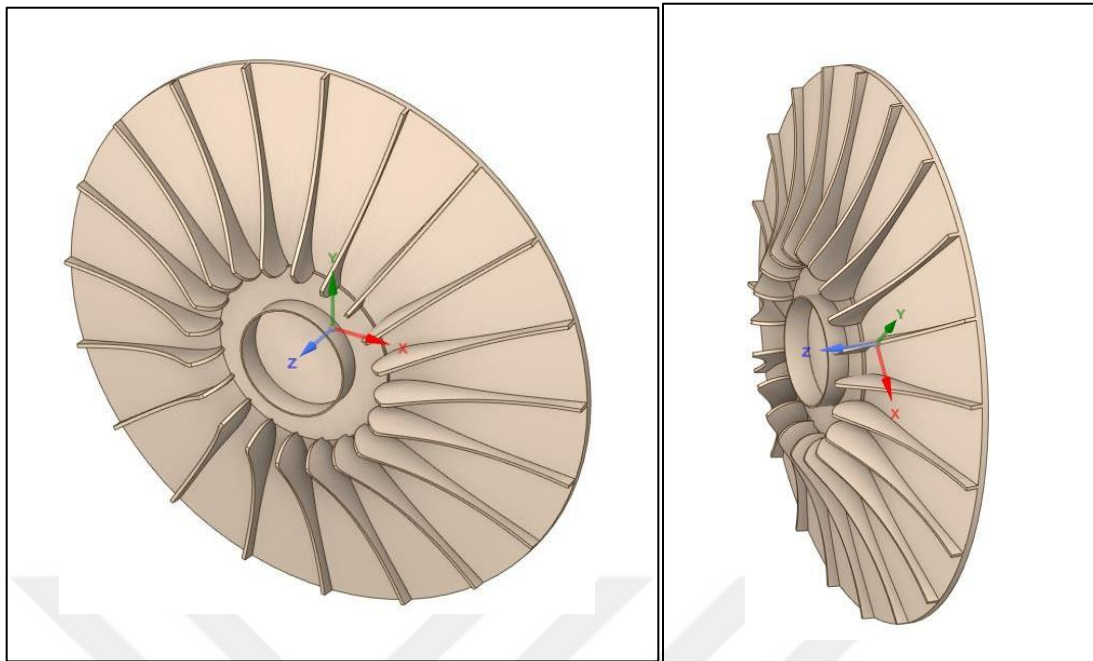


Figure 3.4: Turbine Blade Soldwork.

Table 3.2: Boundary Condition

Bounding Box	
Length X	108.89 mm
Length Y	108.89 mm
Length Z	66.909 mm
Properties	
Volume	19436 mm ³
Mass	0.15257 kg
Scale Factor Value 1.	
Statistics	
Bodies	2
Active Bodies	1
Nodes	36173
Elements	18921
Mesh Metric	None

The inlet turbulence kinetic energy (K.E) was determined based on the reference provided [124]

$$K.E_{in} = 3/2[(T T\%)V]^2 \quad (3.39)$$

The energy dissipation rate at the inlet section has been calculated from [124]

$$\varepsilon = \frac{C\mu(KE)^{3/2}}{L} \quad (3.40)$$

where L is the characteristic length scale and $L = 0.01L_1$, where L_1 is the pitch of the cascade.

The blade in question is a constituent element of either a turbine rotor or stator, and as such, it conforms to a surface of revolution. The flow exhibits periodic symmetry for a given stage with N blades, occurring at an angle of $\theta=360/N$, where N represents the quantity of blades present in each stage. The periodic boundary situations, as illustrated in Figure 1, are characterized by identical and unknown situations at both boundaries. This may be mathematically represented as such:

$$\varphi(Z, R, \theta) = \varphi(Z, R, \theta + 360/N) \quad (3.41)$$

The implementation of a wall function is utilized to enforce the no-slip situation and subsequently reduce the grid resolution in the vicinity of the wall. It is predicted that the velocity vector at nodes located near the solid walls has become parallel to the walls. It is situated at a pre-established distance from the wall. Over this span, the velocity V^+ was dimensionless and can be expressed in the following manner [124]:

$$V^+ = \begin{cases} \frac{V}{\sqrt{\frac{\tau_w}{\rho}}} & \text{for } y^+ \leq 11.5 \\ \{(1/k)\ln(Ey^+)\} & \text{for } y^+ > 11.5 \end{cases} \quad (3.42)$$

where the first node is located at nearly $(0.005 \cdot C)$ from the wall and k, E are law of the wall constants [124].

3.13 FINITE ELEMENT MODEL DESCRIPTION

Substantial variations are computed in the proximity of the inlet and outlet within the regions of the foremost and rear edges. The potential for an imbalance prompted an extension of the

problem domain to enable the flow to develop to some extent prior to the inlet and exit boundaries, as depicted in Figure 3.9. The determination of the periodic boundary position was derived from the pitch of the cascade. The aforementioned entity denotes the axis of symmetry that lies between two consecutive chord lines and is derived from empirical data obtained from an actual turbine stage. The element in question is Fluid 141, which is included in the ANSYS 2012 R2 element library. It possesses the following attributes:

Table 3.3: Materials Characteristics in ANSYS

Material		
Assignment		Structural Steel - With Creep Property
Nonlinear Effects		Yes
Thermal Strain Effects		Yes
Bounding Box		
Length X	108.89 mm	77.001 mm
Length Y	108.89 mm	77.001 mm
Length Z	66.909 mm	12.464 mm
Properties		
Volume	6.0379e+005 mm ³	19436 mm ³
Centroid X	-1.1875e-007 mm	2.7666e-007 mm
Centroid Y	8.576e-010 mm	-4.0915e-009 mm
Centroid Z	6.3436 mm	2.6598 mm
Moment of Inertia Ip1		40.769 kg·mm ²
Moment of Inertia Ip2		40.769 kg·mm ²
Moment of Inertia Ip3		80.308 kg·mm ²
Mass		0.15257 kg
Statistics		
Nodes	0	36173
Elements	0	18921
Mesh Metric		None

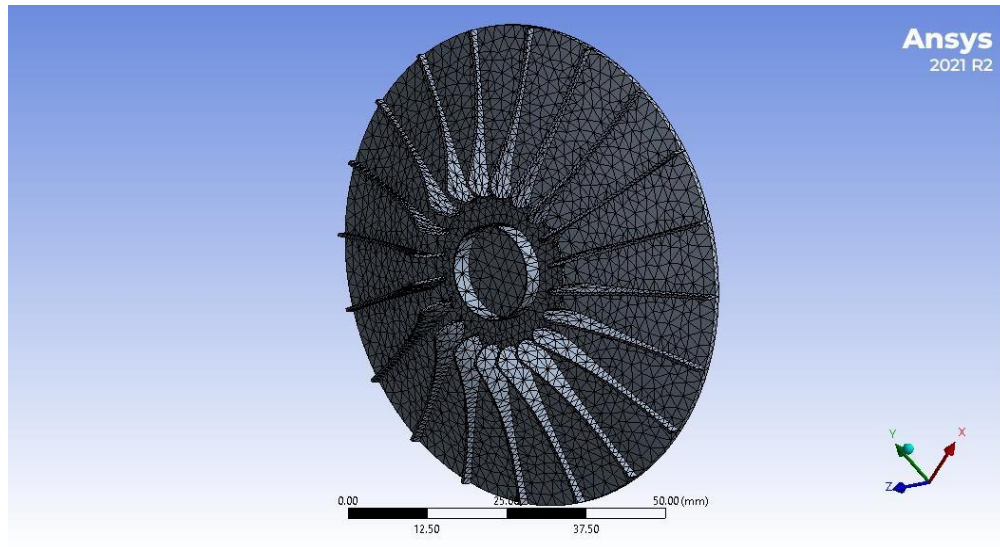


Figure 3.5: Turbine Blades Mesh

Table 3.4: Mesh Properties

Object Name	Mesh
State	Solved
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	2.0 mm
Sizing	
Use Adaptive Sizing	Yes
Resolution	Default (2)
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Diagonal	167.91 mm
Average Surface Area	198.98 mm ²
Minimum Edge Length	2.0108e-003 mm

Table 3.4: Mesh properties "Tables Continued".

Object Name	Mesh
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Aggressive Mechanical
Target Quality Default	(0.050000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Statistics	
Nodes	36173
Elements	18921

Table 3.5: The Cases That Utilized to Simulate the Creep in Gas Turbine

Group	
Thermal condition	800
Imported pressure	0.000176429
Speeding rate	2000 rpm
Case 1	temperature =800° C
Case 2	temperature =1000° C

4. SIMULATION RESULTS AND DISCUSSION

4.1 INTRODUCTION

The current chapter present the obtained results from the simulation of CFD in ANSYS software program.

4.2 NUMBER OF ITERATIONS

Upon confirming the feasibility of a steady state scenario, it is imperative to evaluate the convergence of the solution, detect any anomalies, and ensure that the iteration curves exhibit a seamless pattern [125]. This indicates that the mesh is effectively capturing the flow characteristics. During the initial 5 to 10 iterations, the solution may exhibit non-smooth behavior. However, as the iterative process continues, the velocity and pressure curves tend to become smoother. In a channel flow scenario, it is typical to observe that the u velocity component experiences greater fluctuations during the iterative process when the flow is directed along the x -axis [126]. This phenomenon is expected due to the fact that the flow energy is most concentrated in the x -axis direction. Conversely, the v and w velocity components tend to exhibit similar behavior. Typically, the pressure iteration curve exhibits distinguishable characteristics from the u , v , and w iteration curves. It is imperative to ensure the smoothness of the pressure curve throughout the iteration process. This verification will confirm the suitability of the coarse mesh selection or necessitate the adoption of a medium or fine mesh to mitigate pressure fluctuations.

In relation to the maximum number of iterations, it is noteworthy that the iterations are aimed at achieving the optimal converged solution. For instance, it is possible to observe that the initial 10 iterations may not be smooth, but upon reaching the 20th iteration, the convergence will remain constant without any further changes. This implies that selecting more than 20 iterations would only lead to an increase in the computational time for the simulation, without any significant benefits. Such an action would only result in a delay in meeting the work deadline.

Figure 4.1-4.3 show the iterations number for all selected cases, the obtained results indicated that there is no variation in iterations number in spite of changing the temperature from 800 degree centigrade to 1400 degree.

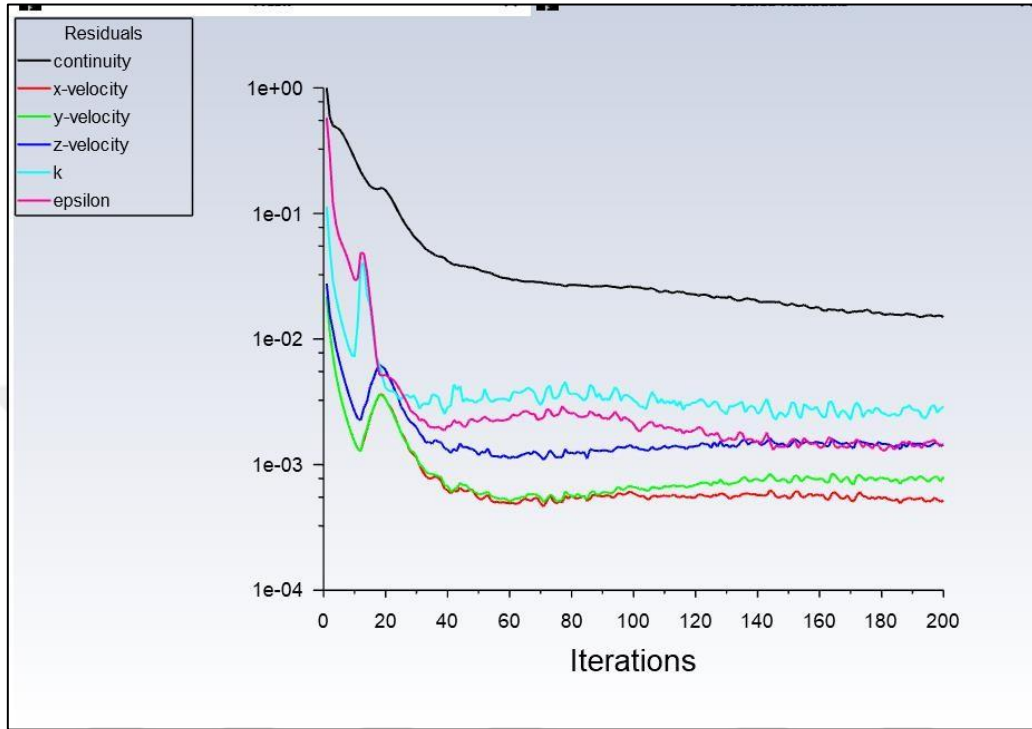


Figure 4.1: Iterations for Case 1 with 800 Degree Centigrade.

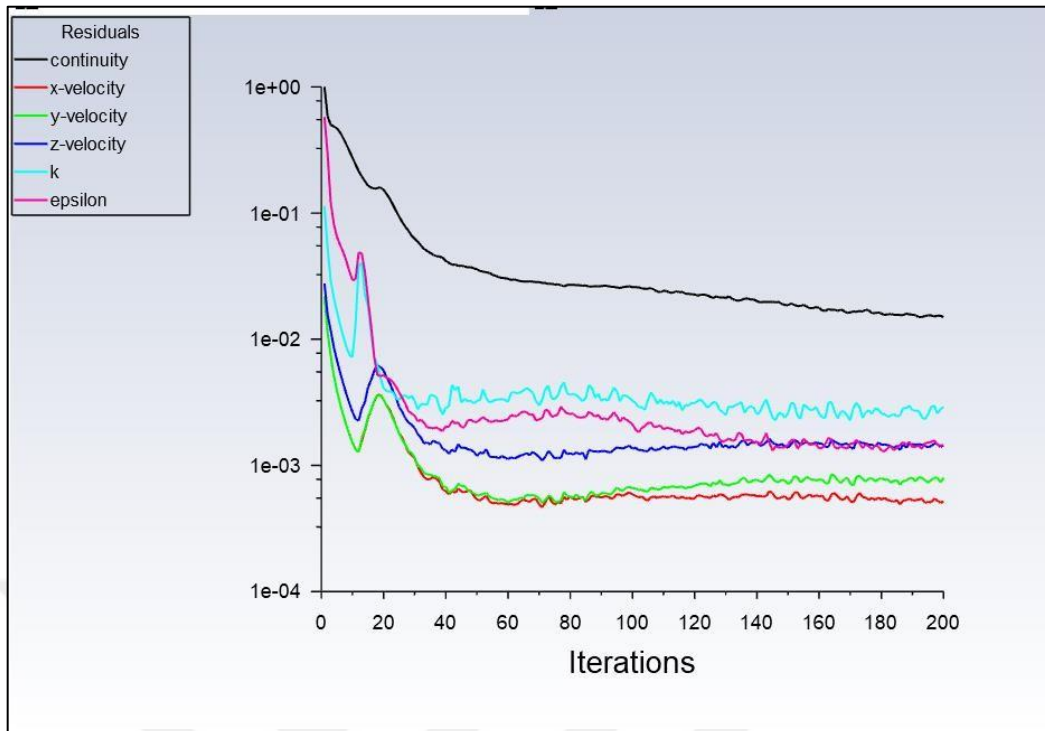


Figure 4.2: Iterations for Case 2 With 1000 Degree Centigrade.

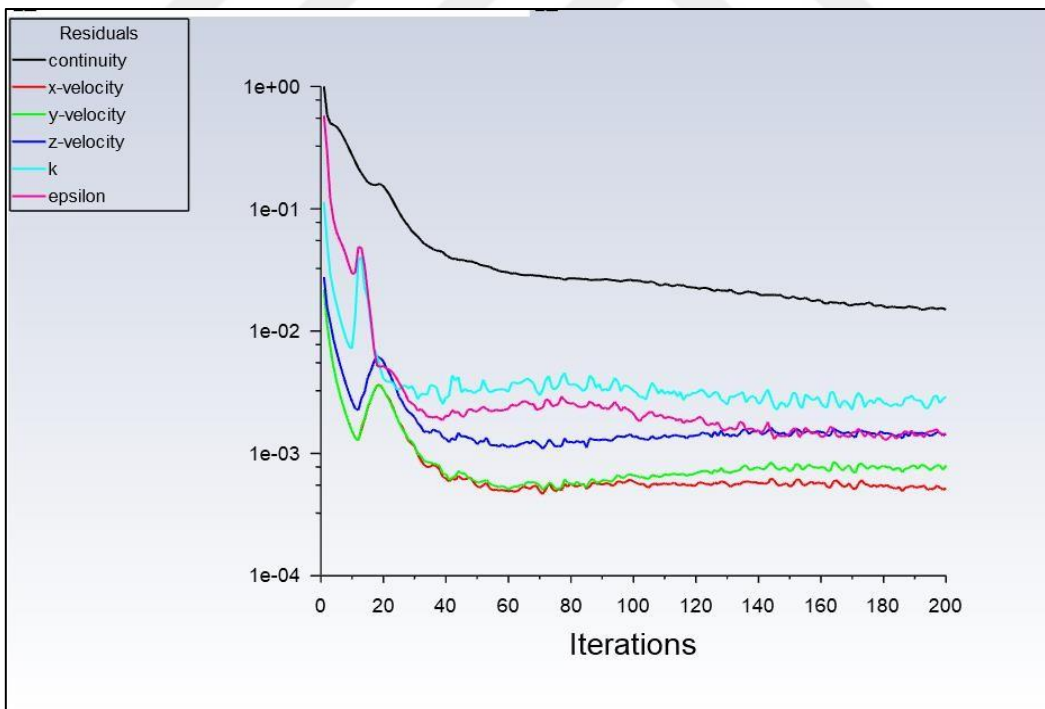


Figure 4.3: Iterations for Case 3 With 1400 Degree Centigrade.

4.3 TOTAL DEFORMATION

The elastic limits that have been delineated earlier are predicated upon uncomplicated tension or uniaxial stress investigations. The findings indicate that materials, especially those that are ductile, exhibit distinct behavior when subjected to non-uniaxial stress or non-simple tension. This behavior is characterized by significantly higher resistance magnitudes compared to those observed in simple tension experimental investigations, as evidenced by previous research [127]. The aforementioned observations led to the formulation of the optimal distortion energy hypothesis. A hypothesis encompassing the entirety of the stress tensor was formulated [128].

A common yielding test for metal and other ductile substances is the von Mises stress. It asserts that when the elements of stress affecting the body are more than the criteria, yielding would take place [129]. When a body is subjected to a body or surface force while in its initial states of unreformed or equilibrium, it undergoes deformation in response to the applied force until it reaches a state of mechanical equilibrium or deformed state, as noted in reference [130]. Externally bodies have exerted surface forces on the body, while internal body forces were generated by a force field, such as gravity [131].

The stress-strain correlations pertain to the associations between the deformation of a body due to strain and the external forces that determine the stress. The associations in question, which are occasionally denoted as constitutive formulas, pertain to the physical attributes that comprise the human anatomy [132].

Figure 4.4-4.6 show the total deformation for gas turbine blades at various applied temperatures (800, 1000 and 1400 degree centigrade). At 800 degrees centigrade the max total deformation on gas turbine blades was 0.392 mm, while increasing the applied temperature to 1000-degree centigrade lead to increase the max total deformation on gas turbine blades to 0.49387 mm. However, the highest max total deformation on gas turbine blades has been obtained when applied 1400 degree centigrade, which was 0.6972 mm.

Figure 4.7 show the relationship between the applied temperature on gas turbine blades and max total deformation, where the relationship was positive and increase one of theme lead to increase the other one.

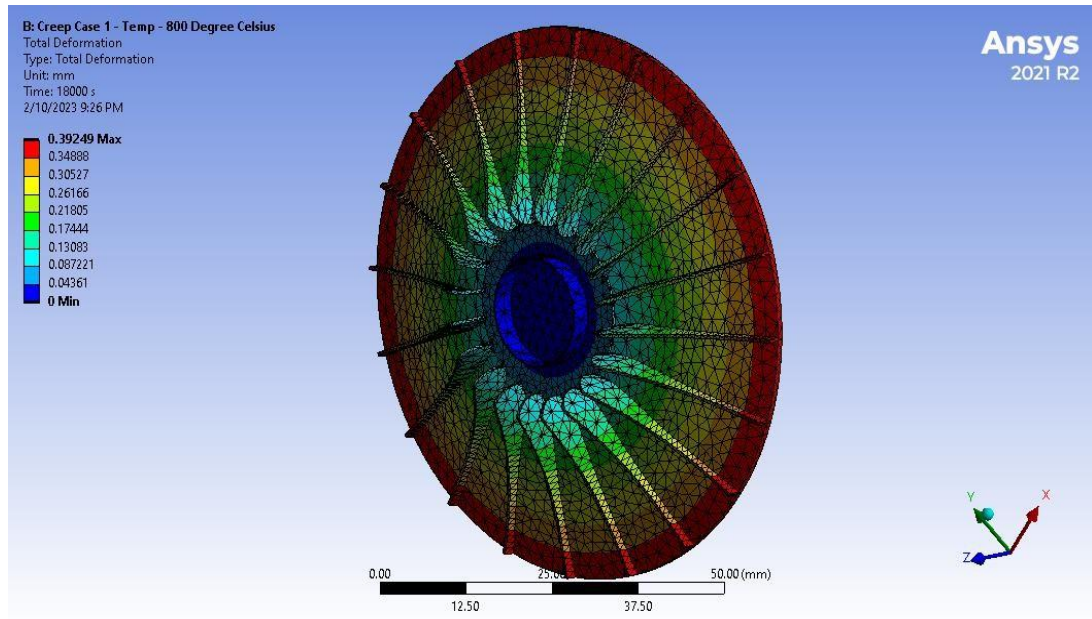


Figure 4.4: Total Deformation for Case 1 with (temperature =800)

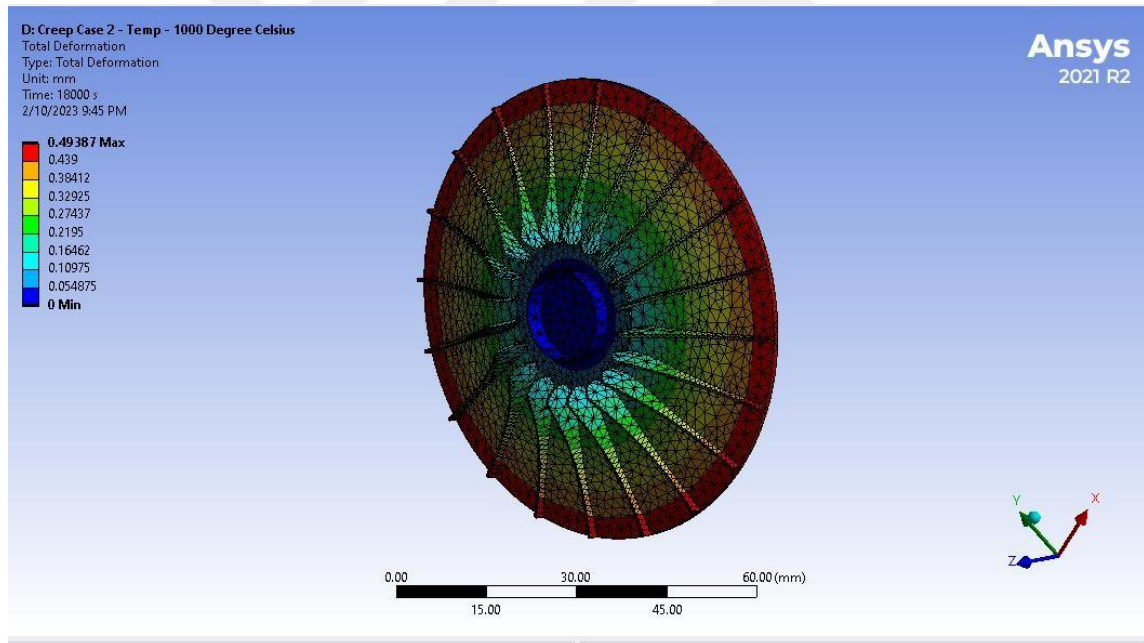


Figure 4.5: Total Deformation for Case 2 with (Temperature =1000)

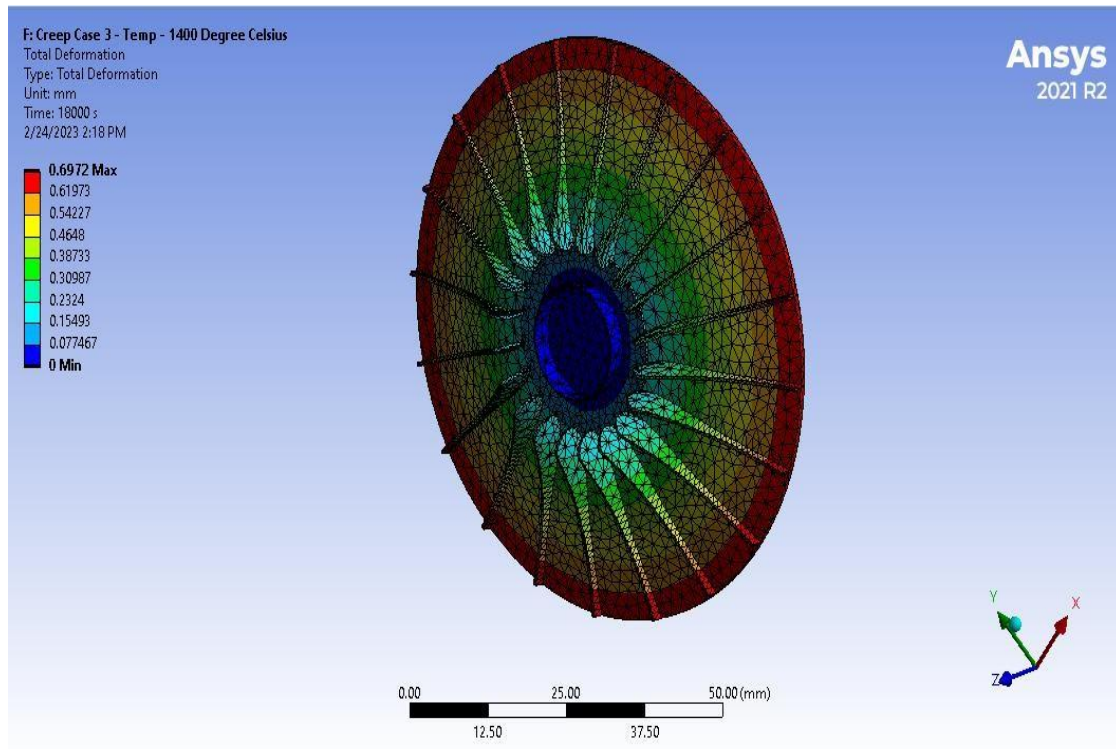


Figure 4.6: Total Deformation for Case 3 with (Temperature =1400)

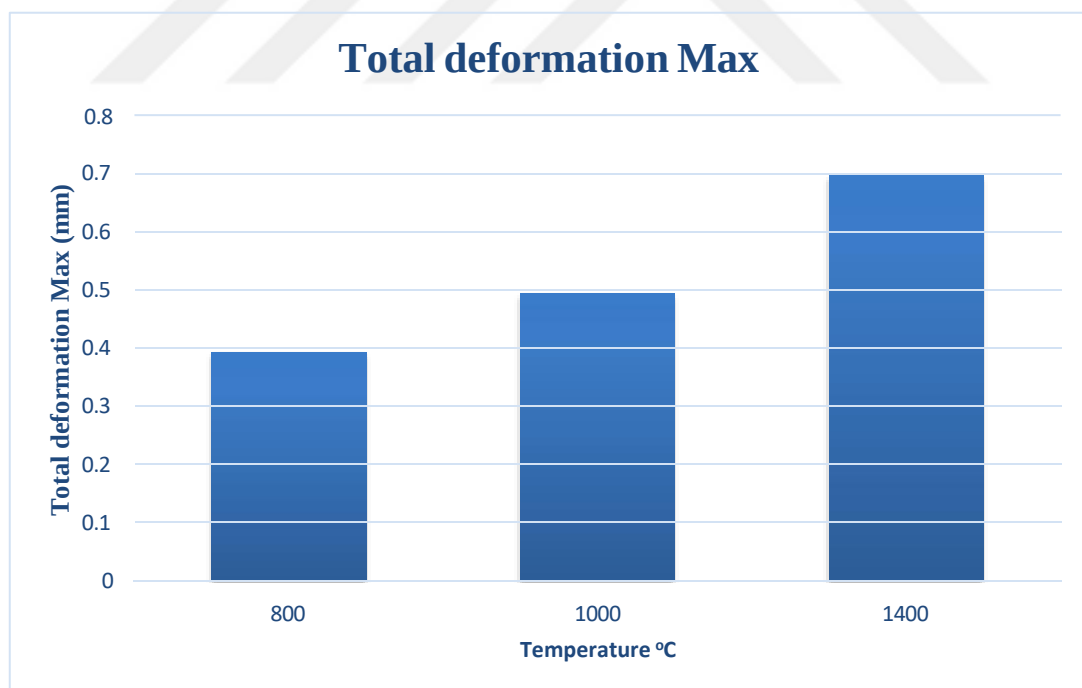


Figure 4.7: Total Deformation for the Selected Temperatures.

4.4 EQUIVALENT (VON MISES) STRESS

The critical magnitude of distortion occurs when a material yields, as per the von Mises stress theory. This phenomenon is recognized under various names including the distortion-energy theory, the shear-energy theory, the octahedral-shear-stress theory, and the Maxwell-Huber-Hencky-von Mises hypothesis. Finite Element Analysis is widely utilized in various applications. By conducting a simple tensile test, it is possible to obtain the essential and distinct property of each material. The von Mises yield criterion is utilized to determine the yielding behavior based on the von Mises stress, which serves as an indicator rather than a direct measure of stress, for failure assessment. The Von Mises stress theory provides a formula, $N = \sigma_y/\sigma'$, which can be utilized to determine the safety factor in relation to failure. The von Mises criteria is often utilized in the assessment of malleable materials to ensure compliance.

In the field of structural engineering and strength of materials, a constituent or member may be vulnerable to various types of forces or moments, or a complex amalgamation of them. Theories pertaining to the phenomenon of failure aim to ascertain the underlying cause behind the inability of a given material to perform its intended function upon surpassing one or more critical thresholds. Each material exhibits a single predominant failure mechanism, rendering all other mechanisms irrelevant. The verification of this is frequently accomplished by employing multiple failure theories across diverse loading scenarios. The notion that accurately predicts failure under diverse conditions is widely acknowledged for such materials. Hence, it is imperative to differentiate between principal stress and von Mises stress. According to the max principal stress hypothesis, a material fails once the main stress it experiences as a result of any loading surpasses the principal stress at which the material fails in a one-dimensional loading test (universal tensile test in the case of mild steel). Furthermore, according to the von Mises failure criterion hypothesis, failure happens once a material's shear strain energy/unit volume under any loading is greater than its shear strain energy/unit volume in a single-dimensional loading (universal tensile test in the case of mild steel). At a certain location in the system, the distortion energy density is determined using Von Mises stress formulas. On the other hand, principal stress is created by appropriately converting (rotating) the stress element such that the rotational element is not susceptible to shear stress. Von Mises criterion may be used to anticipate most ductile material failures. In

contrast, principal stress theory may be applied to brittle materials such as cast iron but has relatively few practical uses. Von Mises stress function has been utilized far more often than primary stress function for defect prediction activities. Main stresses could be readily derived from the von Mises stress function, but von Mises stress magnitudes cannot be used to determine principal stresses.

Figure 4.8-4.10 show the equivalent (Von mises) stress for gas turbine blades at various applied temperatures (800, 1000 and 1400 degree centigrade). At 800 degrees centigrade the equivalent (Von mises) stress on gas turbine blades was 4161.6 MPa, while increasing the applied temperature to 1000-degree centigrade lead to increase the equivalent (Von mises) stress on gas turbine blades to 4546.1 MPa. However, the highest equivalent (Von mises) stress on gas turbine blades has been obtained when applied 1400 degree centigrade, which was 5811.8 MPa.

Figure 4.11 show the relationship between the applied temperature on gas turbine blades and equivalent (Von mises) stress, where the relationship was positive and increase one of theme lead to increase the other one

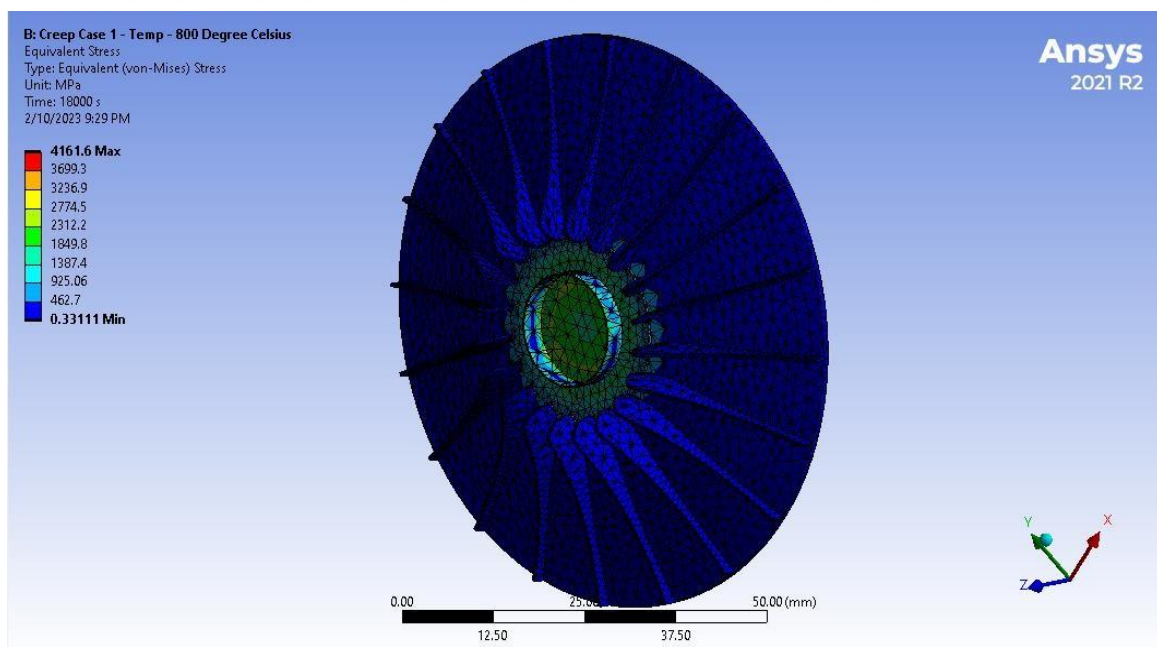


Figure 4.8: Equivalent (Von mises) Stress for Case 1 with (temperature =800).

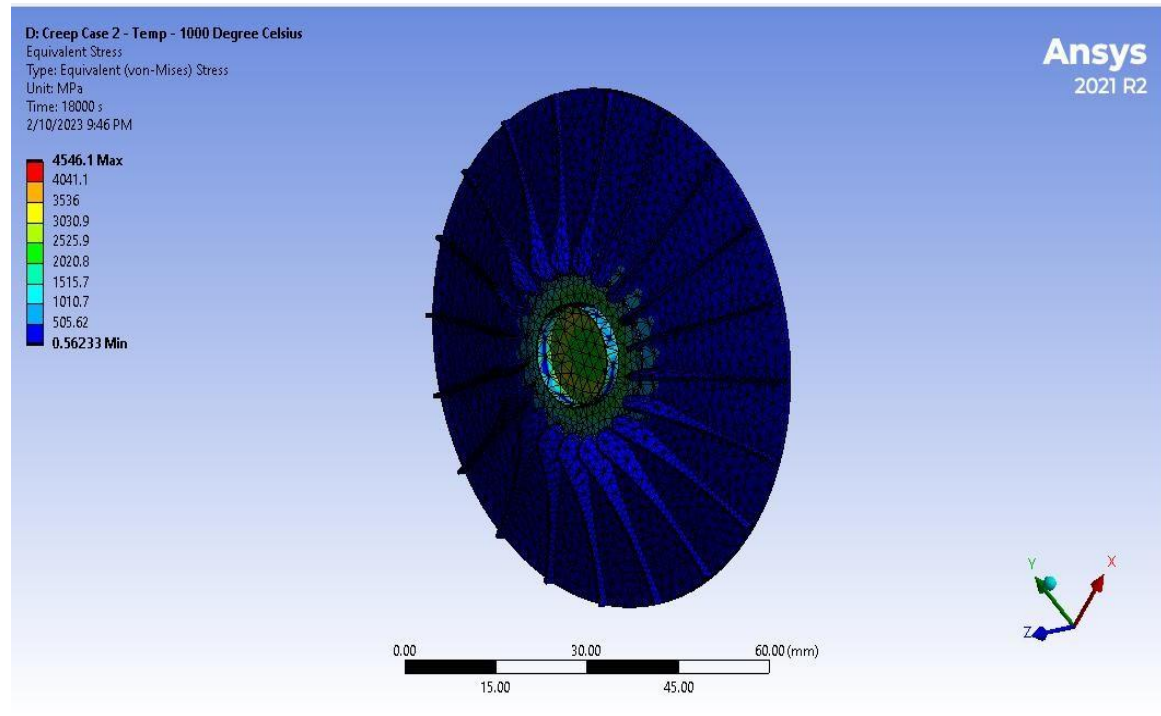


Figure 4.9: Equivalent (Von Mises) Stress for Case 2 With (Temperature =1000)

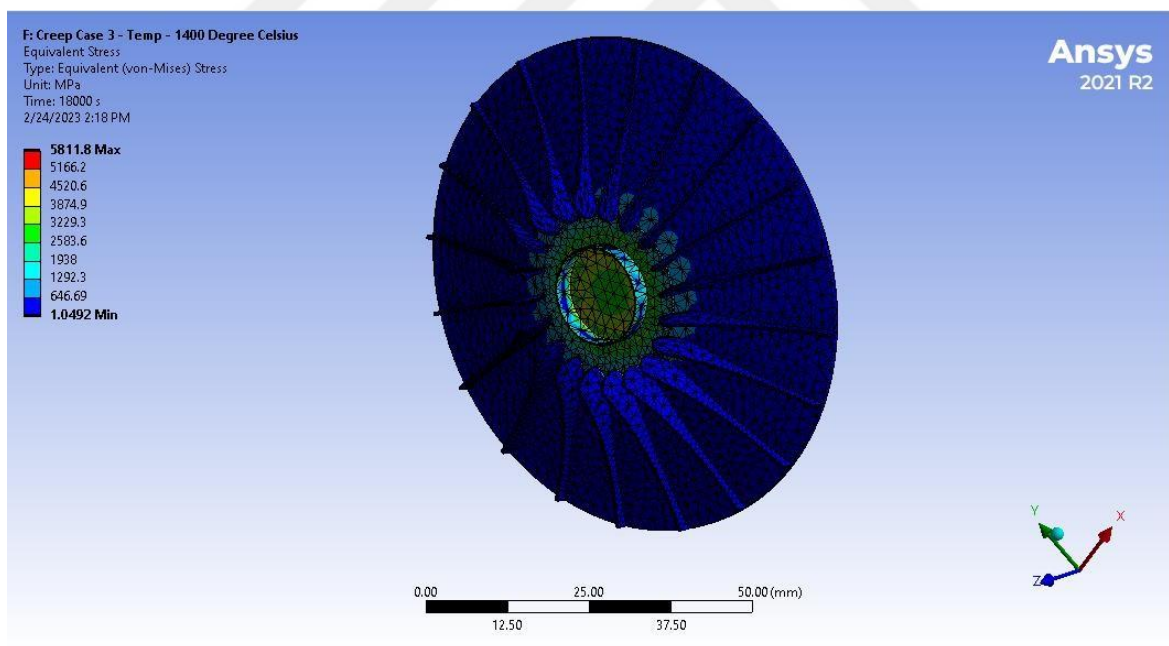


Figure 4.10: Equivalent (Von Mises) Stress for Case 3 with (Temperature =1400)

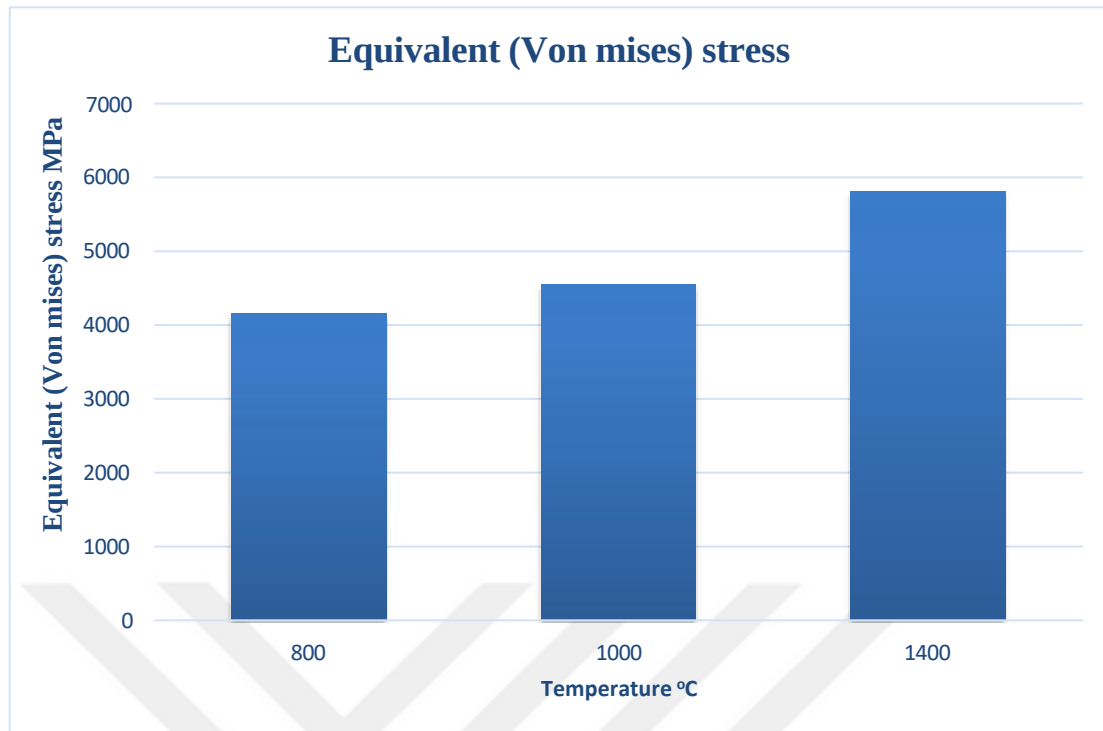


Figure 4.11: Equivalent (Von Mises) Stress for the Selected Temperatures.

4.5 EQUIVALENT CREEP STRAIN

The Creep Rupture Test involves the application of a continuous mechanical load to a test specimen, which is kept at a predetermined temperature. The duration of time until the specimen ruptures is then measured, typically spanning several months or even years [133]. A Creep test bears resemblance to a Creep rupture test, albeit in the former, the elongation of the test specimen is observed throughout the test. The present exposition provides insights into the Creep deformation rate that cannot be obtained through a Creep rupture test [134].

Prior to commencing an analysis, it is imperative to ascertain the need for a Creep deformation analysis. If the sole objective is to guarantee that a constituent does not undergo rupture subsequent to a certain period, then a stress rupture analysis suffices as the necessary measure [135]. The primary inquiry to consider is whether the disproportionate distortion would impede the operation of a constituent. In the event of a turbine blade undergoing excessive Creep deformation, it would initiate contact with the surrounding casing, thereby leading to complications such as wear and vibration. A deformation analysis focused on creep would yield valuable insights in this scenario. Conversely, the reformer tube utilized

in hydrogen production exhibits loose clearances, with the primary consideration being the prevention of Creep rupture within the intended design lifespan. A plausible course of action in this scenario would be to conduct a Creep rupture analysis utilizing a Larson Miller curve [136].

The concept of rate-dependent plasticity pertains to the flow rule of materials, which is contingent upon temporal considerations. It is currently postulated that the deformation of materials occurs in relation to the strain rate or duration. A significant category of applications pertaining to this theory pertains to high temperature creep. ANSYS offers various options for characterizing distinct types of rate-dependent material behaviors. The term "creep option" is utilized to denote the phenomenon of material creep occurring over an extended duration or at a low level of strain. The option of rate-dependent plasticity employs a cohesive creep methodology to explicate the characteristics of materials that are contingent on the rate of strain. The viscoelasticity option proposed by Anand constitutes an additional plasticity model that is dependent on the rate of deformation and is commonly employed in simulations related to metal forming processes. In addition to the pre-existing alternatives, it is possible to integrate a rate-dependent plasticity model as a user-defined material option utilizing the programmable feature.

Figure 4.12-4.14 show the equivalent creep strain for gas turbine blades at various applied temperatures (800, 1000 and 1400 degree centigrade). At 800 degrees centigrade the equivalent creep strain on gas turbine blades was 1.1789×10^{-10} mm/mm, while increasing the applied temperature to 1000-degree centigrade lead to increase the equivalent creep strain on gas turbine blades to 5.7343×10^{-10} mm/mm. However, the highest equivalent creep strain on gas turbine blades has been obtained when applied 1400 degree centigrade, which was 6.0817×10^{-9} mm/mm.

Figure 4.15 show the relationship between the applied temperature on gas turbine blades and equivalent creep strain, where the relationship was positive and increase one of theme lead to increase the other one.

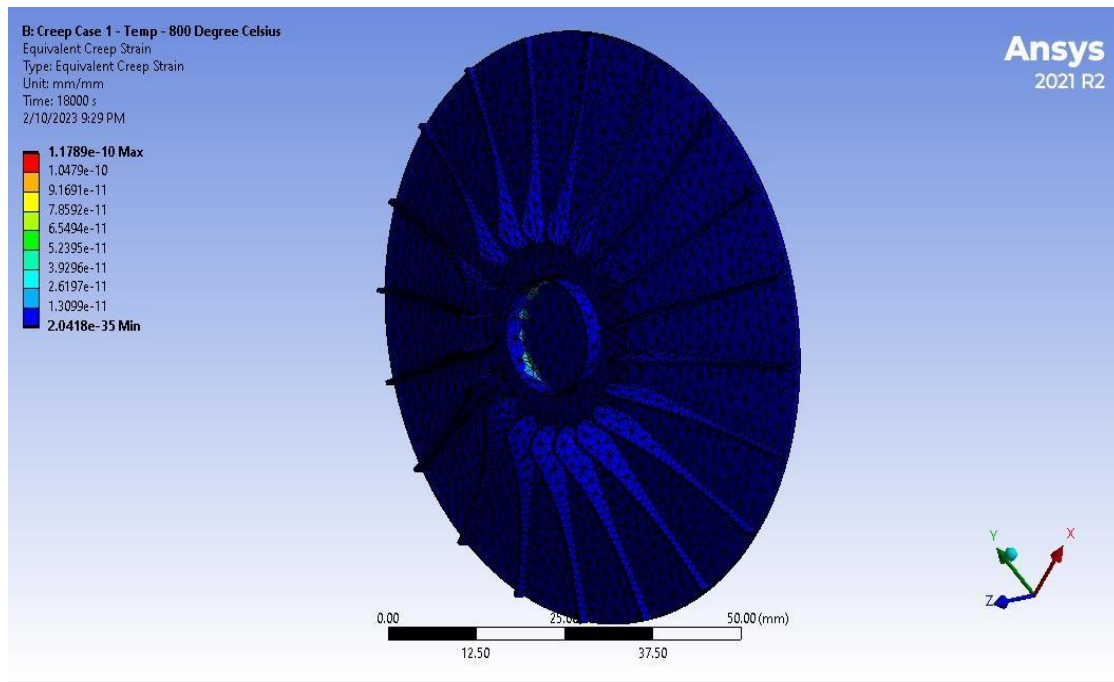


Figure 4.12:Equivalent Creep Strain for case 1 with (Temperature =800)

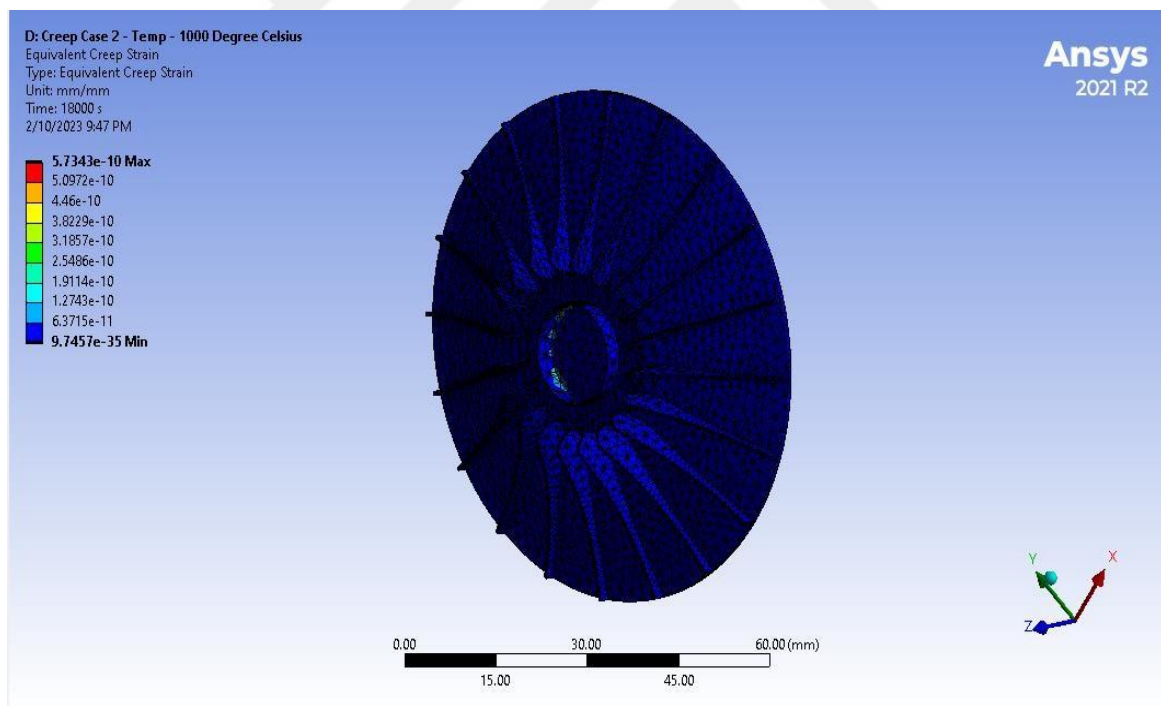


Figure 4.13: Equivalent Creep Strain for Case 2 with (Temperature =1000)

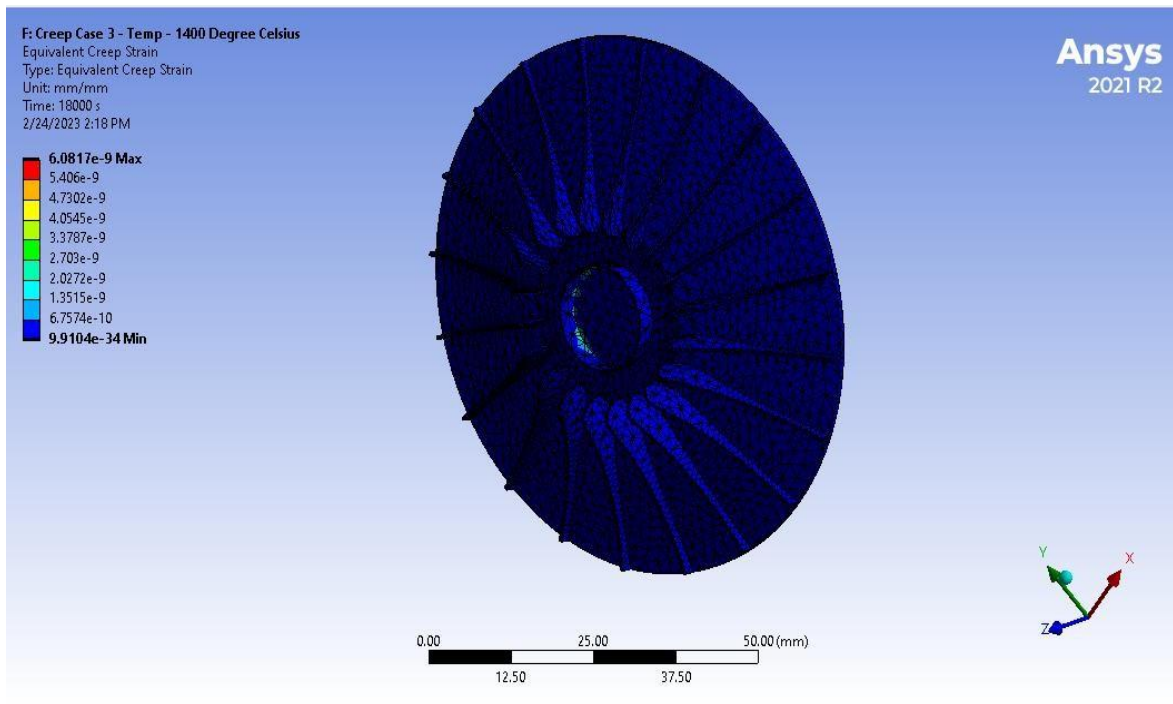


Figure 4.14: Equivalent Creep Strain for Case 3 with (Temperature =1400).

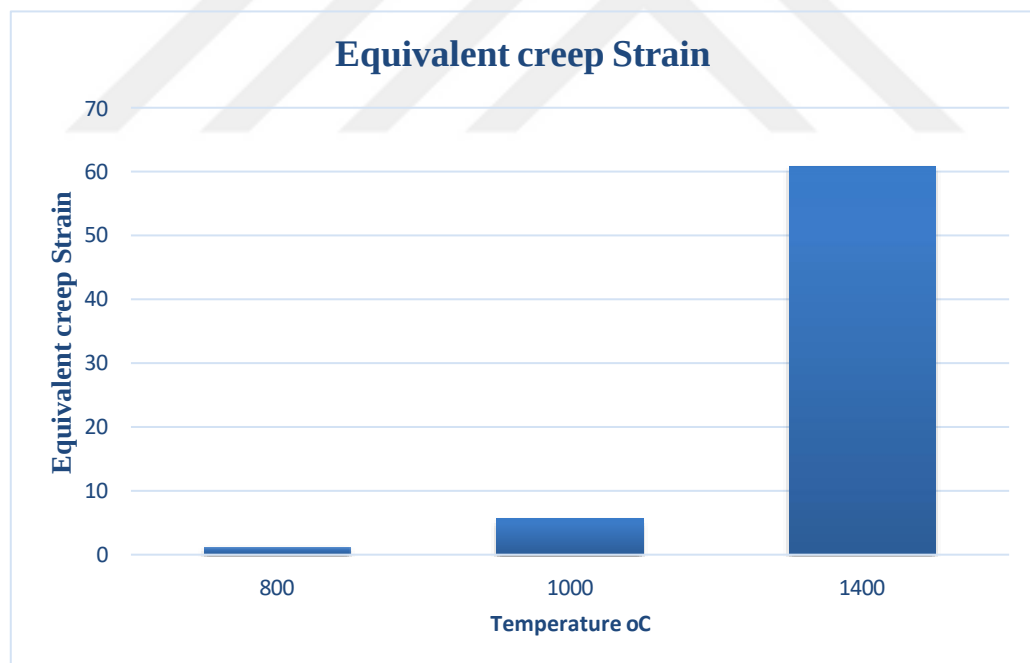


Figure 4.15: Equivalent Creep Strain for the Selected Temperatures.

4.6 VELOCITY

The velocity of gases may be altered by the presence of blades affixed to various components, including turbines, compressors, regenerators, economizers, and other similar devices. Gas turbines are categorized into three distinct groups based on the number of shafts they possess. The gas turbine is a cylindrical machine that features a tricone attachment at its end. In comparison to other turbine or internal combustion engines, they exhibit a superior power-to-weight ratio or efficiency. Gas turbines are considered to be highly reliable compared to other types of turbo machinery due to their minimal number of moving components.

The installation of gas turbines in a power plant is a more convenient and cost-effective option. The installation of a gas turbine in a power plant can be accomplished within approximately 400 days, which is a shorter duration compared to the installation of a nuclear power plant that takes around 1900 days, and a coal plant that takes approximately 1200 days. The utilization of gas turbine as a factor is gaining increasing attention in certain countries. Gas turbines are highly efficient and user-friendly machines that supply power to various industries through a generator attached to their shaft. They are also utilized for powering boats, aircraft, cars, and other modes of transportation, and are gradually replacing traditional internal combustion engines due to their superior cost-effectiveness. The turbines manufactured by Siemens exhibit an efficiency of approximately 90%. It has been observed that the industries or other relevant fields are able to utilize only 45% of the total efficiency of this turbine. The efficiency of a turbine can be enhanced by integrating two distinct types of turbines. The efficiency of a gas turbine is determined by the Brayton cycle and is computed based on this underlying assumption. The gas turbine is comprised of a compressor, turbine, and combustion chamber that are connected to a central shaft. The turbine and compressor components of a gas turbine engine are primarily comprised of blades. These blades are affixed to the compressor and turbine in opposing orientations. Therefore, the blade is a critical element of the gas turbine engine, as modifications to blade geometry can enhance engine efficiency.

Figure 4.16-4.18 show the velocity for gas turbine blades at various applied temperatures (800, 1000 and 1400 degree centigrade). At 800 degrees centigrade the velocity on gas

turbine blades was 15.65 m/s, while increasing the applied temperature to 1000-degree centigrade lead to increase the velocity on gas turbine blades to 21.99 m/s. However, the highest velocity on gas turbine blades has been obtained when applied 1400 degree centigrade, which was 33.14 m/s.

Figure 4.19 shows the relationship between the applied temperature on gas turbine blades and velocity, where the relationship was positive and increase one of theme lead to increase the other one.

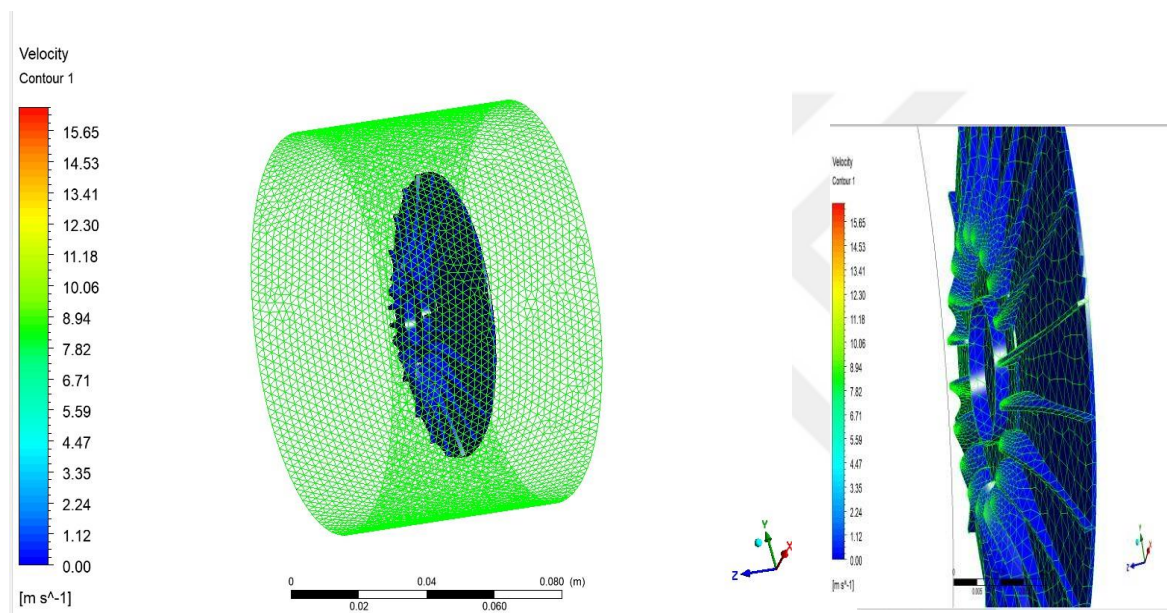


Figure 4.16: Velocity for Case 1 with (Temperature =800)

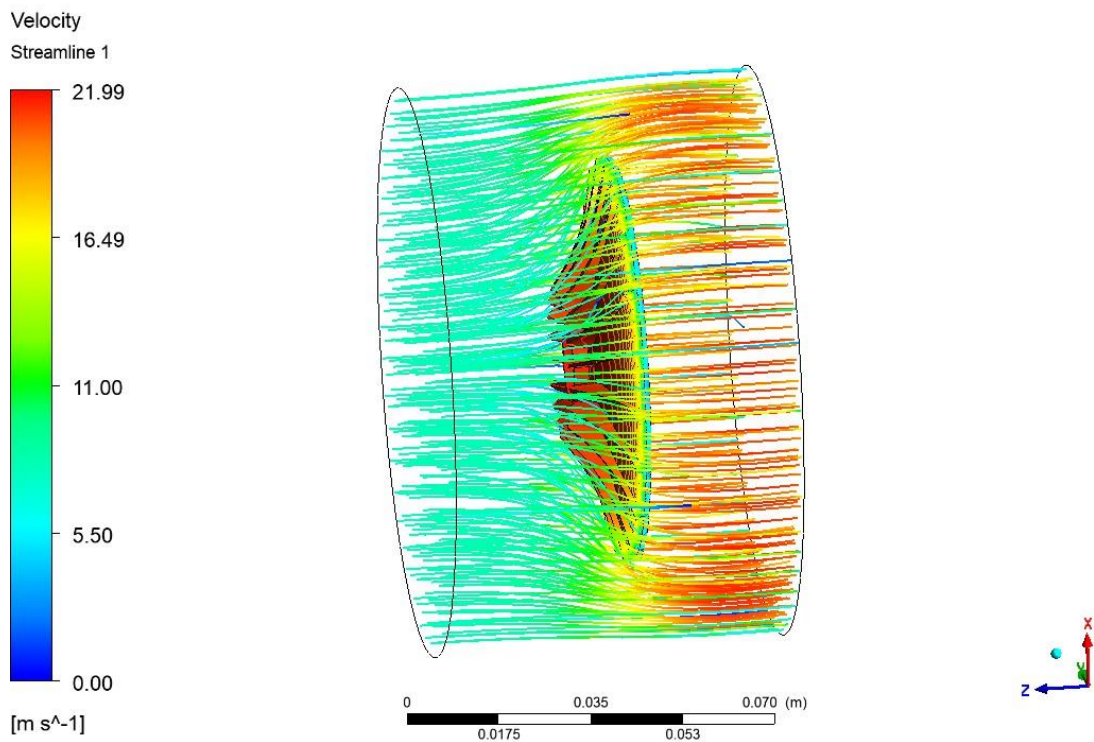


Figure 4.17: Velocity for Case 2 with (Temperature =1000)

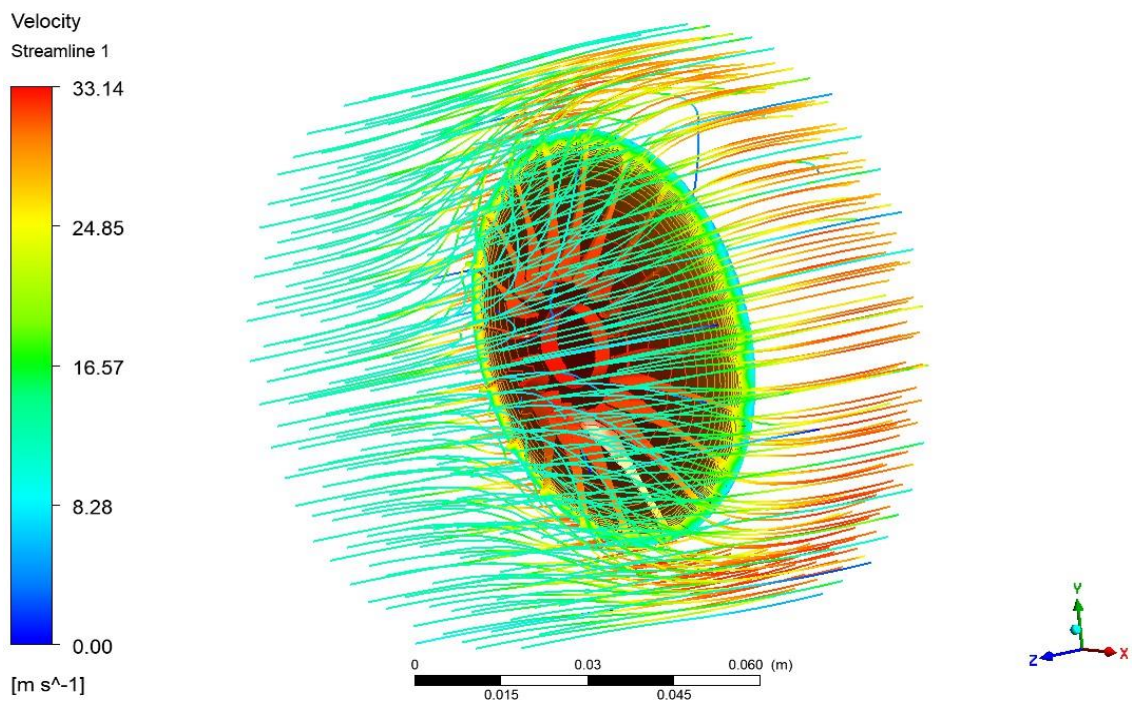


Figure 4.18: Velocity for Case 3 with (Temperature =1400)

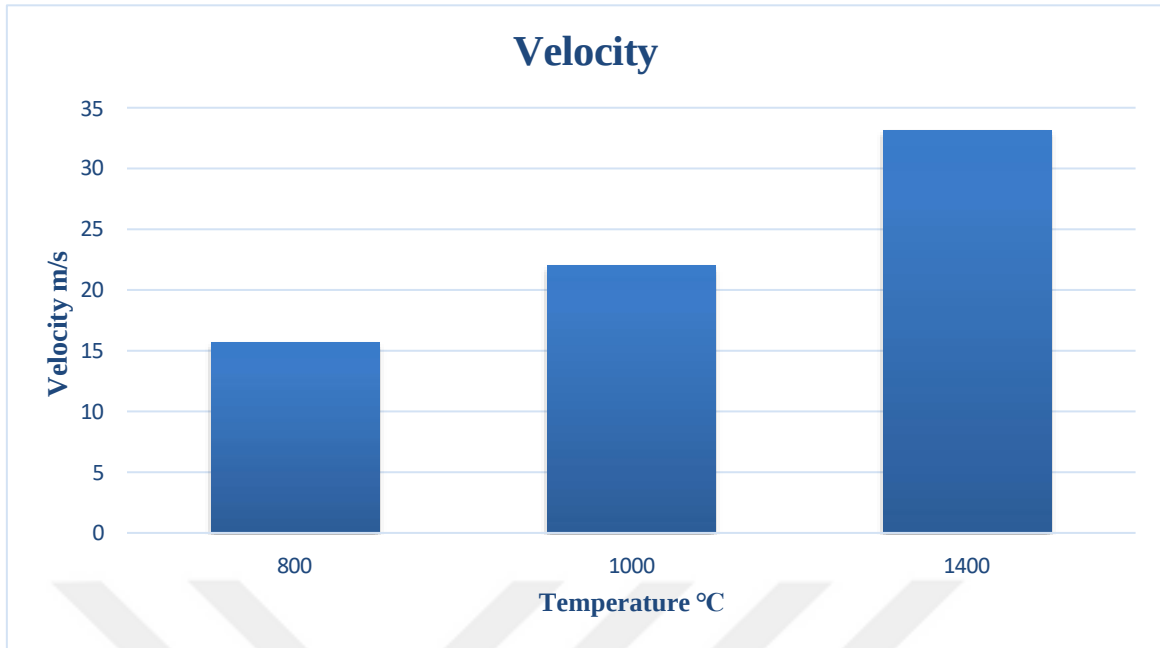


Figure 4.19: Velocity for the Selected Temperatures.

4.7 PRESSURE

In gas turbines, the expansion process is typically initiated by hot gas coming from the combustion system and entering the turbine at a high pressure and temperature. This hot gas then passes through the revolving turbine blades. In order to achieve a higher level of total thermal efficacy and, therefore, a greater level of output, cutting-edge gas turbines have been utilized [137].

Since they are the ones that are in charge of corkscrewing the energy from the elevated temperatures and high-pressure gas entering from the burning chamber or the atmosphere, blades are the most significant component of a turbine [138]. This is because blades are responsible for corkscrewing the energy. The blades of a turbine are not only responsible for converting kinetic energy into mechanical energy, but they are additionally frequently referred to as the fundamental components of a turbine [139].

Figures 4.20-4.22 show the pressure for gas turbine blades at various applied temperatures (800, 1000 and 1400 degree centigrade). At 800 degrees centigrade the pressure on gas turbine blades was 183.21 Pa, while increasing the applied temperature to 1000-degree

centigrade lead to increase the pressure on gas turbine blades to 324.82 Pa. However, the highest pressure on gas turbine blades has been obtained when applied 1400 degree centigrade, which was 731.84 Pa.

Figure 4.23 shows the relationship between the applied temperature on gas turbine blades and pressure, where the relationship was positive and one of them lead to increase the other one.

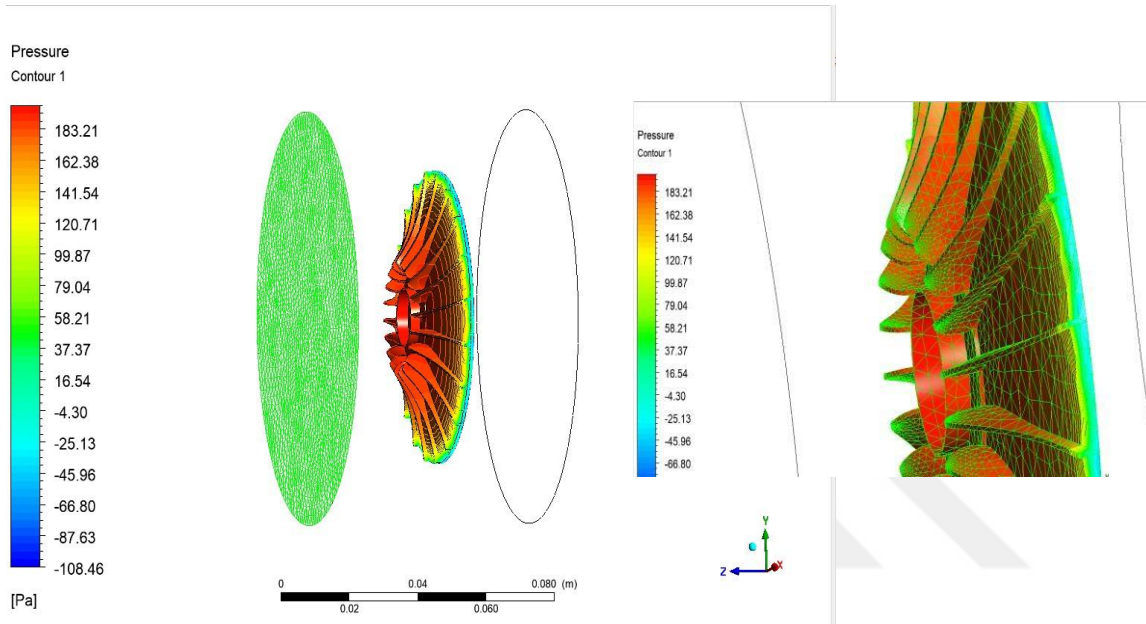


Figure 4.20: Pressure for Case 1 with (Temperature = 800)

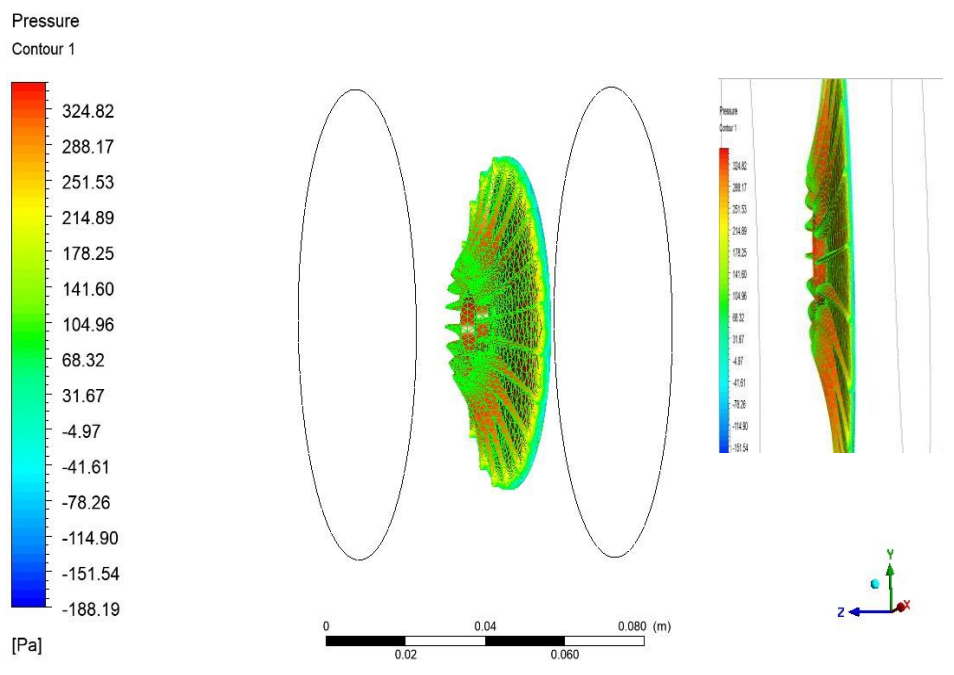


Figure 4.21: Pressure for Case 2 with (Temperature =1000)

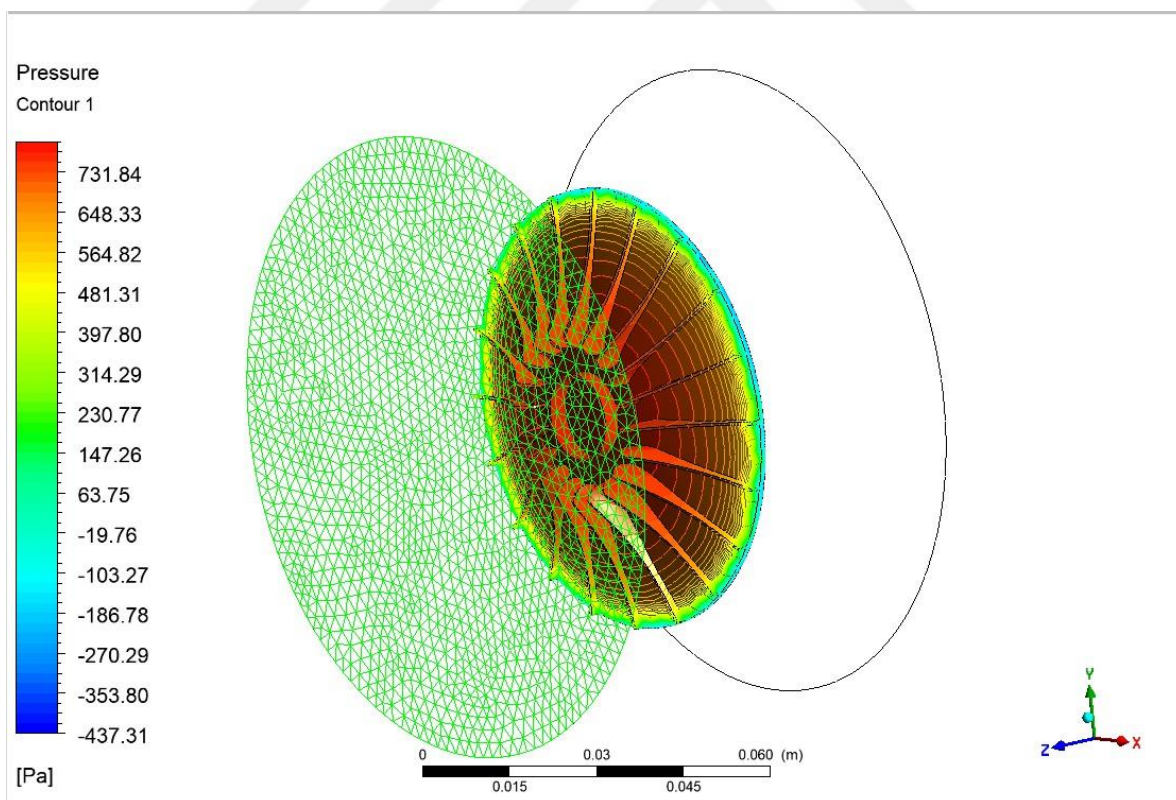


Figure 4.22: Pressure for case 3 with (Temperature =1400)

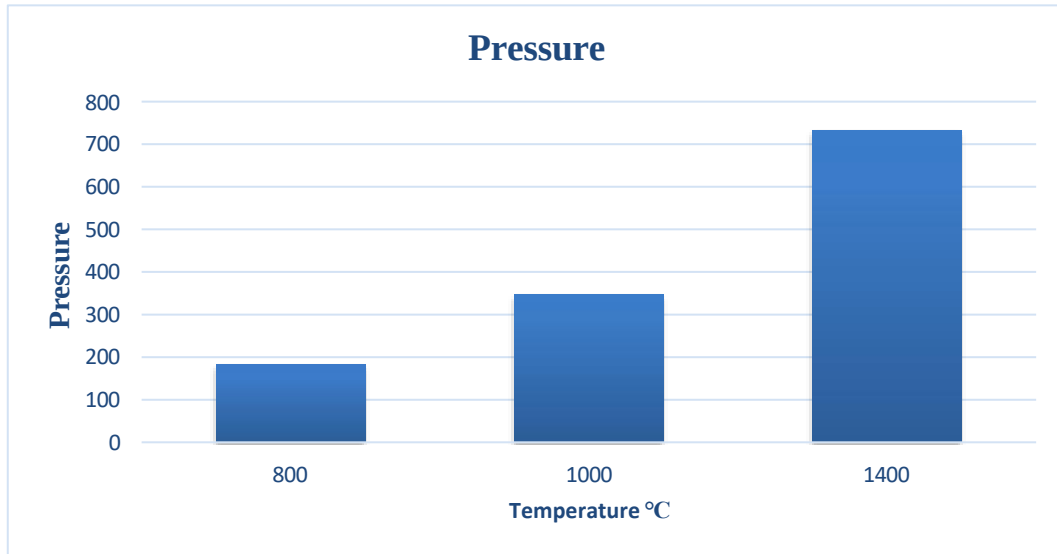


Figure 4.23: Pressure for the Selected Temperatures.

Table 4.1: Summary of the Obtained Results from Simulation by ANSYS Software Program.

Group			
Thermal condition	800	800	800
Imported pressure	0.000176429	0.000176429	0.000176429
Case 1 Speed rate = 1500 rpm			
	Mix	Average	Min
Total deformation	0.39249	0.196245	0
Equivalent (Von mises) stress	4161.6	2080.965555	0.33111
Equivalent creep Strain	1.1789×10^{-10}	5.8945×10^{-11}	2.0418×10^{-35}
Pressure	183.21	37.375	-108.46
Velocity	15.65	7.825	0
Case 2 Speed rate = 2000 rpm			
Total deformation	0.49387	0.246935	0
Equivalent (Von mises) stress	4546.1	2273.331165	0.56233
Equivalent creep Strain	5.7343×10^{-10}	2.86715×10^{-10}	9.7457×10^{-35}
Pressure	347.82	79.63	-188.19
Velocity	21.99	10.995	0

Table 4.1: Summary of the Obtained Results from Simulation by ANSYS Software Program

“ Tables Continued ”.

Group			
Case 3 Speed rate = 3000 rpm			
Total deformation	0.6972	0.3486	0
Equivalent (Von mises) stress	5811.8	2906.4246	1.0492
Equivalent creep Strain	6.0817×10^{-9}	3.04085×10^{-9}	9.9104×10^{-34}
Pressure	731.84	147.265	-437.31
Velocity	33.14	16.57	0

5. CONCLUSION AND FUTURE RESEARCH SUGGESTIONS

5.1 CONCLUSION

The pursuit of enhancing the overall performance of turbines through research and implementation of novel ideas is gaining momentum, given the ongoing developments in technology. The introduction of advanced materials and thermal science in the development of more efficient engines has consistently driven innovation and presented new prospects for companies to enhance their product offerings.

The present paper proposes a numerical methodology for predicting the lifetime of a turbine blade subjected to creep damage. This approach is subsequently employed to predict the lifetime of a high-pressure turbine blade. The current methodology has the capability to provide a direct assessment of the progression of stress in elements, deformation due to creep, and damage in elements. This feature is highly advantageous in the prognostication of the lifespan of high-temp structures.

Based on the obtained results the gas turbine blades will work efficiently under 800 and 1000 degree centigrade, while increasing the temperature to 1400 degree centigrade will lead to fail the blades due to increase the total deformation to more than double as well as increase the pressure to more than trouble comparison with applying 800 degree centigrade.

5.2 RECOMMENDATIONS

- i. It is recommended to allocate additional resources towards the implementation of advanced technology for the purpose of scanning and inspecting turbine blades with greater efficiency. This approach has the potential to significantly reduce the duration of manual inspections required for each blade. The enhancement of realism in x-ray or exterior scanning techniques is imperative for the improvement of accuracy and reduction of the duration between testing and obtaining results.
- ii. The utilization of composite materials in the turbine section as a substitute for conventional super alloys is a promising approach to enhance the power-to-weight proportion and reduce maintenance expenses, owing to their lightweight and durable nature. Ceramic composites possess inherent performance capabilities that render them superior to super alloys in the turbine section, owing to their lighter weight and greater thermal stability.
- iii. Further investigation is recommended regarding the development of enhanced containment mechanisms aimed at mitigating potential hazards resulting from the failure of engine components, particularly the turbine section.
- iv. The study of turbine blades has been advanced with the development of novel materials that exhibit high melting points, thermal conductivities, and varying densities. This is particularly relevant given the increasing utilization of turbines in industrial settings, where maximizing efficacy is imperative due to the depletion of resources over time.

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