

**T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL**

**SOLID PARTICLE EROSION TESTING ON
TURBINE BLADE**

AYHAN İSMAİL KIRCA

**A THESIS OF MASTER OF SCIENCE DEPARTMENT OF
ENERGY TECHNOLOGIES IN APPLIED PROPULSION
SYSTEM DESIGN & ENGINEERING FOR AEROSPACE
TECHNOLOGIES**

ADVISOR: PROF. DR. İLYAS KANDEMİR

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

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ABSTRACT

Erosion is an important factor that causes damage to engine components, decrease in engine efficiency and decrease in flight safety in gas turbine engines.

Erosion occurs when small particles such as dirt, sand or dust enter the engine and collide with engine components at high speeds. The impact of these particles can cause erosion, which can lead to pitting, cracking, and other damage to engine components.

The secondary air system is an important part of the gas turbine engine. It is responsible for providing cooling and sealing of various parts of the engine, especially the hot part. The secondary air system typically consists of a network of tubes, ducts, and nozzles that direct cool air to specific parts of the engine.

In this study, high-pressure turbine blades were pressurized with air from the blade root and simultaneously sandblasted with 220 grit aluminum oxide. In this way, the effect of secondary air flow on erosion damage was tried to be observed. In this study, experiments were carried out to observe the effect of the angle of the cooling holes on the blade surface on erosion damage.

As a result of the experiments, it has been seen that the secondary air flow can have erosion-reducing effects if it is given at the appropriate angle.

Keywords: Erosion, Turbine Blade, Cooling Hole, Secondary Air Flow.

ÖZET

Erozyon, gaz türbinli motorlarda motor bileşenlerinin hasarlanmasına, motor veriminin düşmesine ve uçuş emniyetinin azalmasına sebep olan önemli bir faktördür. Erozyon, kir, kum veya toz gibi küçük parçacıkların motora girmesi ve yüksek hızlarda motor bileşenleriyle çarpışması sonucu oluşur. Bu parçacıkların etkisi erozyona neden olabilir ve bu da motor bileşenlerinde çukurlaşma, çatlama ve diğer hasarlara yol açabilir.

İkincil hava sistemi gaz türbinli motorun önemli bir parçasıdır. Başta sıcak kısım olmak üzere motorun çeşitli parçalarının soğutulmasını ve sızdırmazlığını sağlamaktan sorumludur. İkincil hava sistemi tipik olarak soğuk havayı motorun belirli bölümlerine yönlendiren bir tüpler, kanallar ve nozullar ağından oluşur.

Bu çalışmada, yüksek basınçlı türbin kanatlarına kanat kökünden gelen hava ile basınç uygulanmış ve eş zamanlı olarak 220 gritlik alüminyum oksit ile kumlama yapılmıştır. Bu sayede, ikincil hava akışının erozyon hasarı üzerindeki etkisi gözlemlenmeye çalışılmıştır. Bu çalışmada bıçak yüzeyindeki soğutma deliklerinin açısının erozyon hasarına etkisini gözlemlemek üzere deneyler gerçekleştirilmiştir.

Deneyler sonucunda uygun açı ile sevk edilmesi halinde, ikincil hava akışının erozyon hasarını azaltıcı etkilere sahip olduğu görülmüştür.

Anahtar Kelimeler: Erozyon, Türbin Kanatçıkları, Soğutma Deliği, İkincil Hava Akışı

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LIST OF SYMBOLS AND ABBREVIATIONS

A	: Area
W	: Amount of Erosion
F	: Force
m	: Mass
P	: Pressure
V	: Speed
EDM	: Electrical Discharge Machining
FOD	: Foreign Object Damage
HPC	: High Pressure Compressor
HPT	: High Pressure Turbine
LPC	: Low Pressure Compressor
LPT	: Low pressure Turbine
LPC	: Low Pressure Compressor
MW	Megawatt
PSI	: Pounds Per Square Inch
TBC	: Thermal Barrier Coating
TIT	: Turbine Inlet Temperature

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1. INTRODUCTION

Gas turbine engines have a long history dating back to the early 19th century. The first patents for gas turbine engines were granted in the late 19th century, but the first practical gas turbine engines were not developed until the 1930s.

One of the early pioneers of gas turbine technology was an Englishman named Alan Arnold Griffith. In 1926, Griffith published a paper on the potential of gas turbine engines, in which he outlined the basic principles of how a gas turbine engine works. He also built a small, experimental gas turbine engine that proved the feasibility of the design.

However, the first practical gas turbine engines were not developed until the 1930s. In 1939, the German engineering firm Junkers built the Jumo 004, the first gas turbine-powered aircraft [1]. The Jumo 004 was a major breakthrough in aviation as it was much more powerful and efficient than the piston engines commonly used at the time.

After World War II, the development of gas turbine engines continued rapidly. In the 1950s, General Electric and Pratt & Whitney developed large, commercial gas turbine engines used to power aircraft. These engines were much more powerful and efficient than the piston engines of the past, allowing for much faster and longer flights.

Gas turbine engines were also developed for use in land vehicles in the 1960s and 1970s. The first gas turbine powered car was built by Chrysler in the early 1960s, but the design was never put into production. However, gas turbine engines were later used to power tanks and other military vehicles.

During the 1980s and 1990s, gas turbine technology continued to improve. New materials and manufacturing techniques were developed that allowed the construction of smaller, more efficient gas turbine engines. Additionally, advances in computer technology have enabled the development of new control systems that make gas turbine engines more reliable and efficient. With developing technology, the usage areas of gas turbine engines are expanding. The historical development of gas turbine engines is given in **Figure 1.1** in terms of the relationship between turbine rotor inlet temperature and specific core power [2].

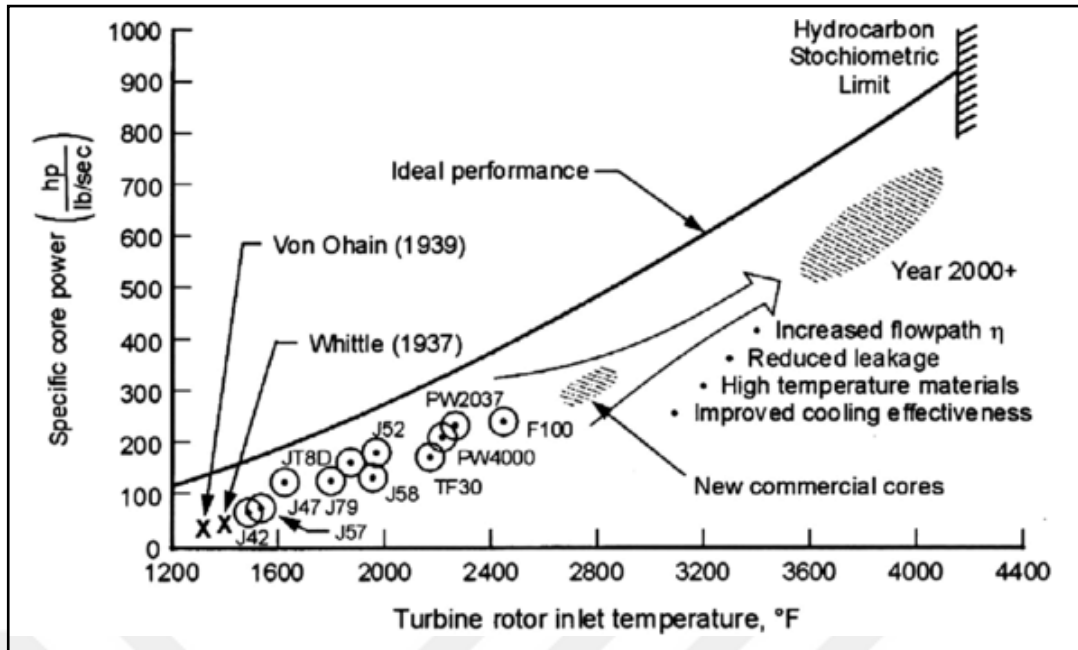


Figure 1.1: The History of Gas Turbine Engines.

Today, gas turbine engines are used in a wide variety of applications, from powering airplanes and helicopters to generating electricity in power plants. They are also used on ships, tanks and other military vehicles. With ongoing research and development, the future of gas turbine engines looks even more promising as they are developed to be more efficient, durable, and economically viable.

1.1. Motivation of Research

Erosion damage, which is one of the most common damage types in engine maintenance operations, is of great importance due to its destructive effects such as causing crack initiation and reducing engine efficiency. Its importance was once again understood after the aircraft engines were rapidly damaged in dusty conditions during the Gulf operation [3].

In the literature research on erosion, it was seen that the studies on erosion in gas turbine engines were largely about volcanic dust and molten particles, and there were few studies on solid particle damage. It has been understood that most of these few studies are theoretical studies. It was evaluated that a system similar to the anti-ice system could be successful in preventing erosion, and it was considered whether a system that could be put into operation by sacrificing some engine power in dusty conditions in order to protect engine materials was considered.

In this study, in order to better understand and prevent erosion damage, which constitutes a significant part of engine damage, it was examined whether solid particle erosion could be reduced by secondary air flow flowing through the blade, ignoring temperature effects.



2. BACKGROUND OF THE STUDY

2.1. Gas Turbine Engines

Gas turbine engines, a type of internal combustion engine, were originally developed for use in military aircraft, but are now used in many sectors, especially civil airline transportation. The gas turbine engine, patented by Frank Whittle in 1930, is considered the first jet engine to produce thrust [4].

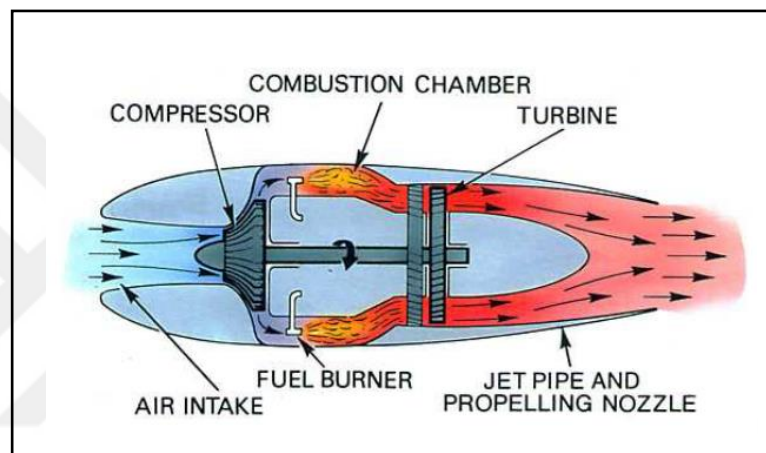


Figure 2.1: Gas Turbine Engine and Basic Modules.

Although there are many different types according to their intended use and design, gas turbine engines basically consist of three basic modules. These are the compressor where air is compressed, the combustion chamber where high-pressure air is burned with fuel, and the turbine where useful work is produced to turn the compressor. Although they are basically similar to piston engines in terms of operating logic, in gas turbine engines intake, compression, combustion and exhaust occur simultaneously and continuously. In piston engines, the piston can produce power in only one out of every four revolutions. This allows gas turbine engines to consume more fuel in a shorter time and produce much more power at the same volume than a piston engine. A gas turbine engine and its basic modules are presented in **Figure 2.1**.

2.2. Gas Turbine Engine Types

One of the references used in the classification of gas turbine engines is their usage areas. The usage areas of gas turbine engines, which have a wide usage area, can be classified as mechanical propulsion production, power generation and aircraft thrust production [5]. Aero-derivative engines are mostly used for mechanical drive production. These motors are generally used in various industries for pump or compressor drive.

Gas turbine engines used for power generation are used in a wide range from 2 MW to 600 MW. Similarly, aero derivative gas turbine engines are used for power generation purposes. Aero power plant gas turbines, from which some power plant gas turbines are derived, are presented in **Figure 2.2** [6].

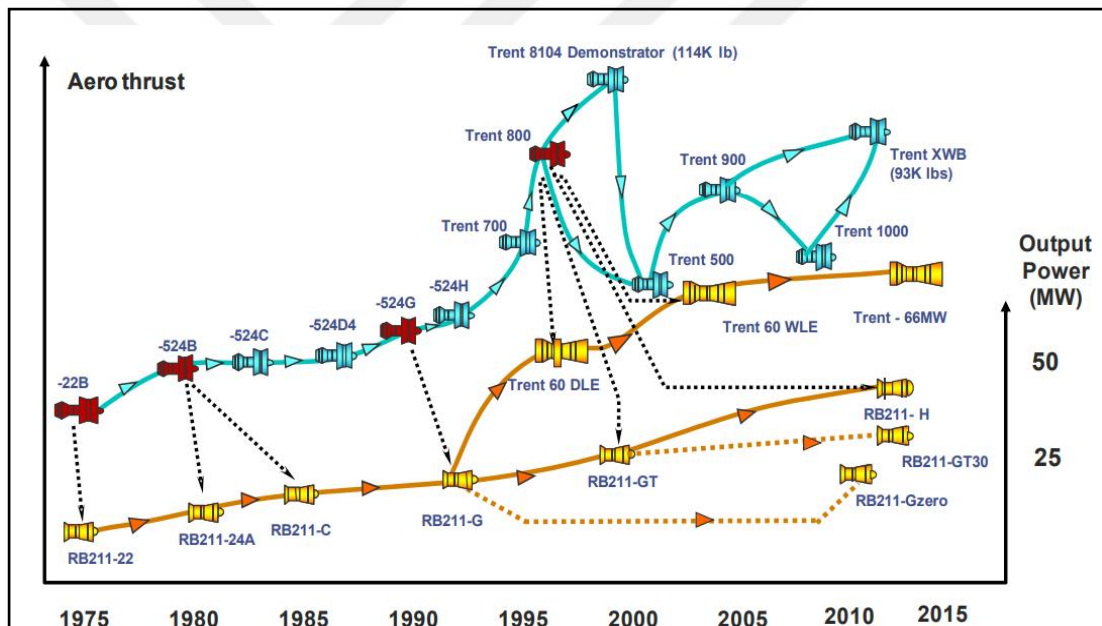


Figure 2.2: Aero-Derivative Engines.

Manufacturers and users prefer to derive a single design to serve more than one purpose, as the aviation industry pioneers the developing technology, maintenance and repair activities are experienced, engines have proven themselves in different geographical and climatic conditions due to the nature of the transportation sector, and engine design costs are high.

Engines used as aircraft propulsion systems can be divided into propeller and jet engines according to the way the thrust is produced. Engines in which thrust is produced by a propeller are divided into two as turboprop and turboshaft. On the other hand, jet engines are divided into two: turbojet and turbofan engines.

2.2.1. Turbojet Engines

Turbojet engines are engines used for thrust production. Turbojet engines form the basis of gas turbine engines with their operating systems based on the principle that the air entering the engine air intake is compressed in the compressor and then burned in the combustion chamber and the hot gases turn the turbine. Propulsion generation occurs by passing the high-pressure gases at the turbine exit through the engine nozzle and expelling them at high speed [7]. The air entering a jet engine is compressed a little more at each stage until it reaches the combustion chamber and is burned in the combustion chamber. The progression of pressure values from low to high pressure can be seen in **Figure 2.3** [8].

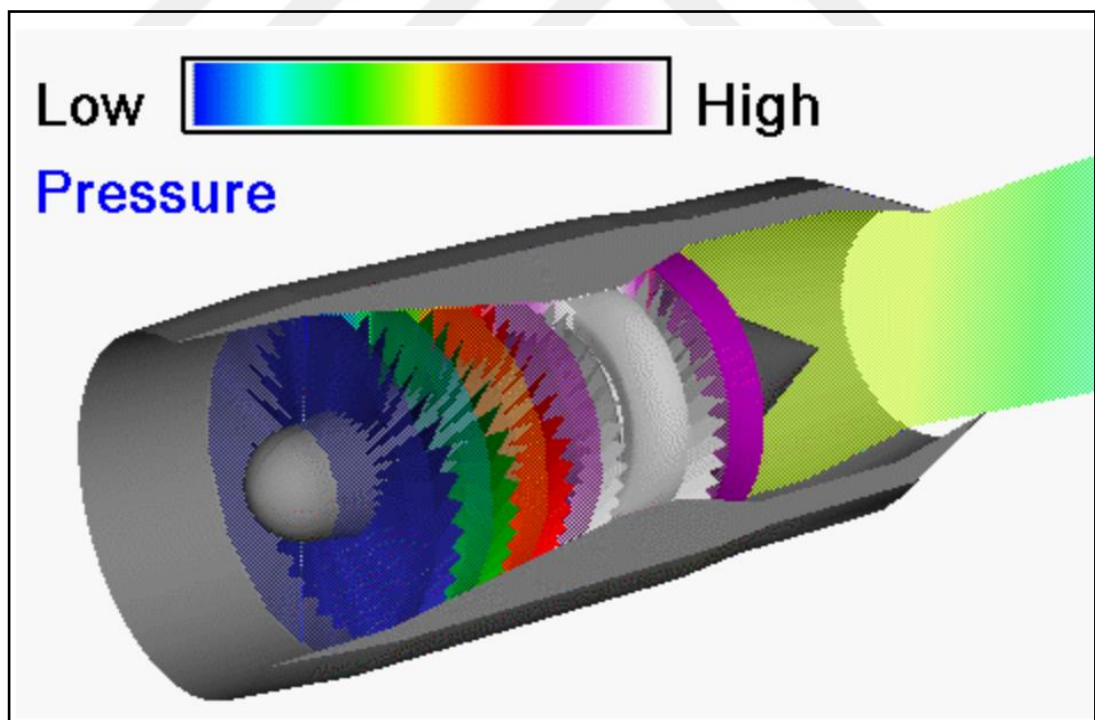


Figure 2.3: Turbojet Engine Pressure Level.

Centrifugal or axial compressors are divided into separate classes according to their use in compressing air. In some applications, centrifugal and axial compressors can be used together. The use of centrifugal compressors provides the advantage of higher compression rates in fewer stages. However, the gradual use of centrifugal compressors is not suitable in terms of efficiency. For this reason, axial compressors with multiple stages are preferred to achieve high compression rates. In the J79-GE-19 engine produced by General Electric, a 12:1 compression ratio was achieved by using a 17-stage compressor [9].

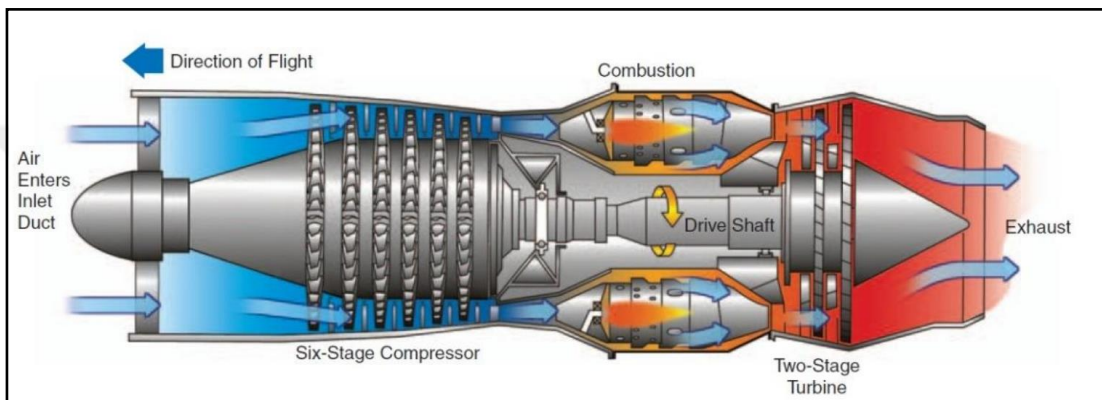


Figure 2.4: Turbojet Engine [10].

Turbojet engines have low propulsive efficiency at low altitudes and low speeds. For this reason, aircraft with Turbojet engines need long runways. To meet this requirement, a second combustion chamber afterburner is added at the turbine exit to increase the thrust during takeoff and sudden acceleration in the air. In this case, the thrust increases by fifty percent, but fuel consumption and noise will also increase.

Turbojet engines have been widely used in warplanes due to their increased efficiency at high altitudes and high speeds. With the developing technology, Turbojet engine applications have become less preferred due to their high fuel consumption, high noise and relatively decreasing efficiency at low altitude. However, among all the various gas turbine engines, turbojet engines, as the most basic form of gas turbine engines, hold an important place in the aviation industry. One way or another, the way to produce thrust is through turbojet engines.

2.2.2. Turboprop Engines

Turboprop engines are basically created by placing an independent turbine driving a propeller at the turbine outlet of turbojet engines. There is a reduction gearbox between the turbine and the propeller. Generally, the turbine driving the propeller is independent, but it is also available in applications where it is directly connected to the compressor rotor shaft.

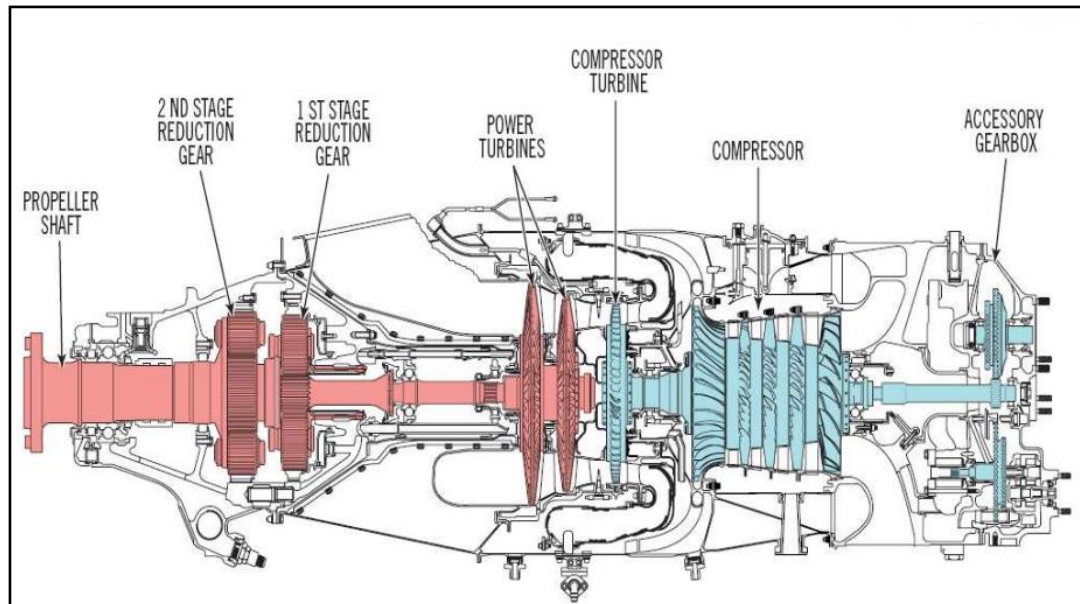


Figure 2.5: PT6A Engine [11].

In turboprop engines, the energy of the exhaust gases is absorbed as much as possible to drive the propeller. For this reason, the gases coming out of the engine exhaust make less noise than turbojet engines. Turboprop engines are more complex and more difficult to maintain than turbojet engines. However, their efficiency is high at low speed and low altitude.

2.2.3. Turboshaft Engines

Turboshaft engines are structurally very similar to turboprop engines; the difference is that turboshaft engines drive a shaft, not a propeller. In most designs, an independent turbine is added to the turbojet engine outlet. This turbine produces shaft power. Being mechanically independent is a design convenience that allows the shaft to be rotated at different speeds with the core motor. The shaft power obtained is used in practice in

vehicles such as hovercraft, helicopters, ship propellers and tanks. The conversion of shaft speed to the desired speed range and direction is provided by the gearbox. Turboshaft manufacturers often design their engines so that they can be used as both turboshaft and turboprop. The turbo shaft engine structured **Figure 2.6** was also introduced [12].

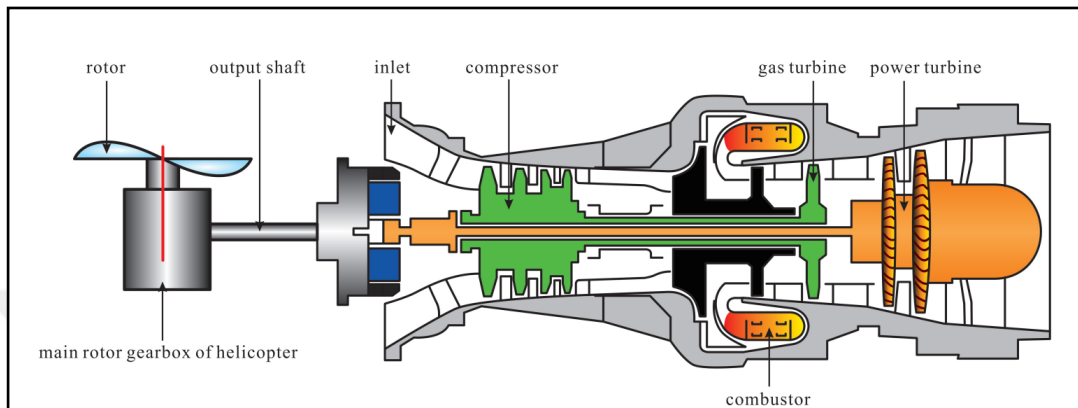


Figure 2.6: Structure of Turboshaft Engine.

2.2.4. Turbofan Engines

Turbofan engines were created by hybridizing turbojet engines and turboprop engines. They are basically created by adding a shaft passed through the middle of a turbojet engine core, a turbine at the back of the engine, and a fan in front of the engine. This fan is often surrounded by a duct. The fan in front of the engine receives its speed directly from the turbine at the back of the engine, without the need for a gearbox. This system is called twin spool. Core engine compressor and turbine are called high pressure compressor (HPC) and high-pressure turbine (HPT). The fan is called low pressure compressor (LPC) and the turbine to which it is connected is called low pressure turbine (LPT).

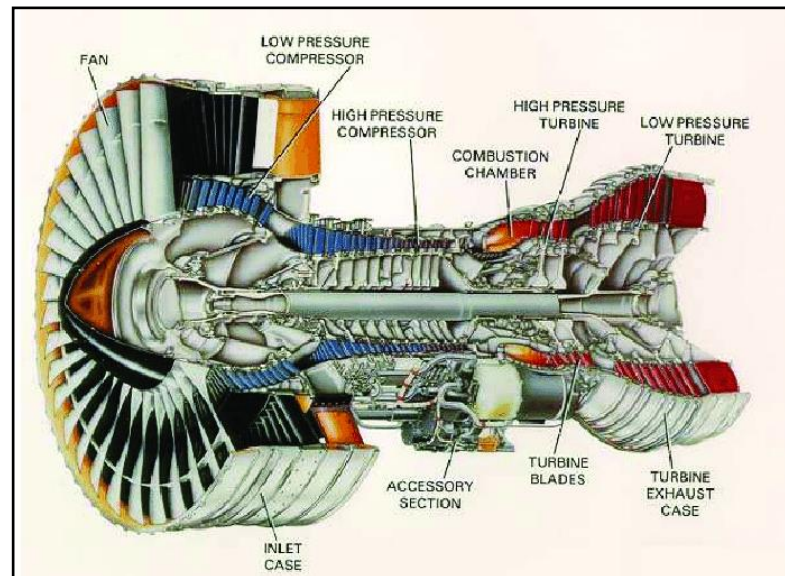


Figure 2.7: Cross Section of a Commercial Turbofan Engine [13].

Similar to the turboprop engine, it has a relatively simpler design as it does not have a gearbox, although it has a propeller in front of the engine. In turbofan engines, the ratio of the air flow passing through the fan stages to the air flow passing through the core engine is called bypass ratio. Turbofan engines are divided into two as low and high bypass ratio turbofan engines.

In turbofan engines with high bypass ratio, the fan part is considerably larger than the core part, as seen in **Figure 2.7**. Most of the engine thrust is obtained from the fan section and such engines provide high fuel economy. The air that releases its energy to the LPT rotor to ensure fan rotation leaves the engine exhaust more slowly, therefore turbofan engines have lower noise levels compared to turbojet engines of the same power. They are increasingly preferred in civil aviation due to their low fuel consumption, low noise and high efficiency.

In turbofan engines with low bypass ratio, the fan section is relatively smaller and the fan section works like a kind of low-pressure compressor. Most of the thrust is produced by the core engine. These types of engines are frequently used in military applications. By attaching an afterburner to the rear of the engine, fan air and turbine outlet air are mixed in a mixing duct and burned again. Another factor that makes turbofan engines stand out is the ability to control the air speed passing through the fan thanks to the engine inlet design. In this way, the responsive efficiency of turboprop engines, which decreases at high speeds, is overcome in turbofan engines. A cross-section of a low bypass ratio turbofan engine can be seen in **Figure 2.8** [14].

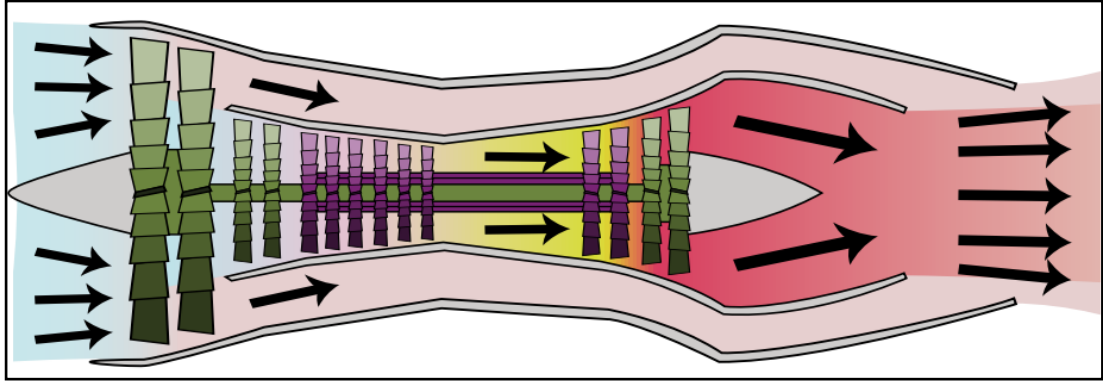


Figure 2.8: Cross-Section of a Military Turbofan Engine.

Turbofan engines have both high reaction efficiency like turboprop engines and high speed and high-altitude capability like turbojet engines. The responsive efficiencies of different engine types can be seen in **Figure 2.9** [15]. These features take them to a more important point in military and civil aviation applications with each passing year.

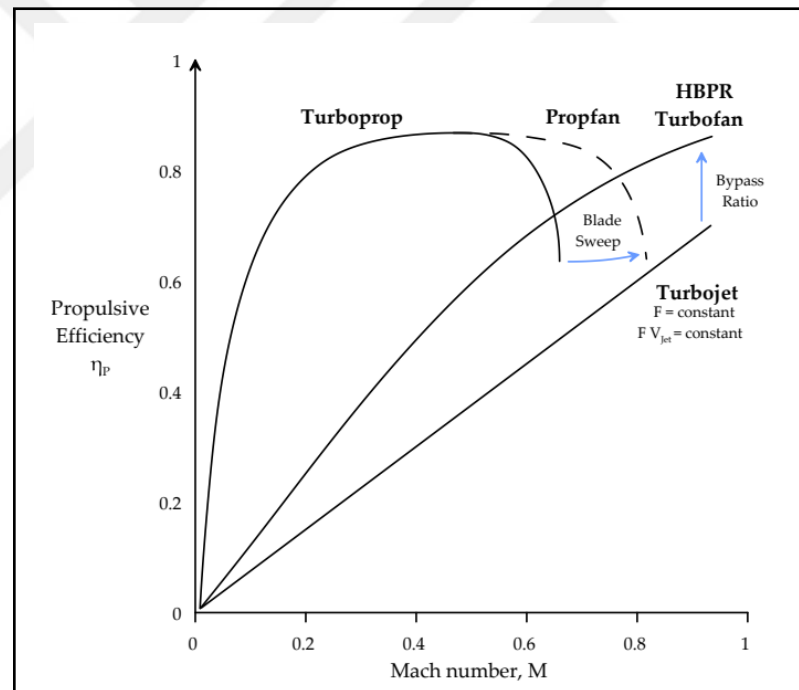


Figure 2.9: Propulsive Efficiency for Different Engine Types.

2.3. Gas Turbine Engine Working Principal

The working principle of gas turbine engines is basically based on the use of air to produce the required thrust. Force or Impulse is the change in the momentum of the

mass. This change can be expressed as the change in the mass and speed of the object between time t_2 and time t_1 .

$$F = [(m.V)_2 - (m.V)_1] / (t_2 - t_1) \quad (2.1)$$

We can use the mass flow rate at the mass site. Since the mass flow rate gives the change of mass with time, the equation simplifies as follows.

$$F = \dot{m}_2.V_2 - \dot{m}_1.V_1 \quad (2.2)$$

Since pressure changes in the flow will cause additional momentum changes, the equation should be updated as follows.

$$F = \dot{m}_2.V_2 - \dot{m}_1.V_1 + (P_2 - P_1).A_2 \quad (2.3)$$

The thrust calculation to be produced by a gas turbine engine is done in its simplest form as above. The air entering from one end of the engine will gain a certain speed and exit from the other end of the engine. At the same time, the exit of the air, whose pressure also changes, will create a thrust force.

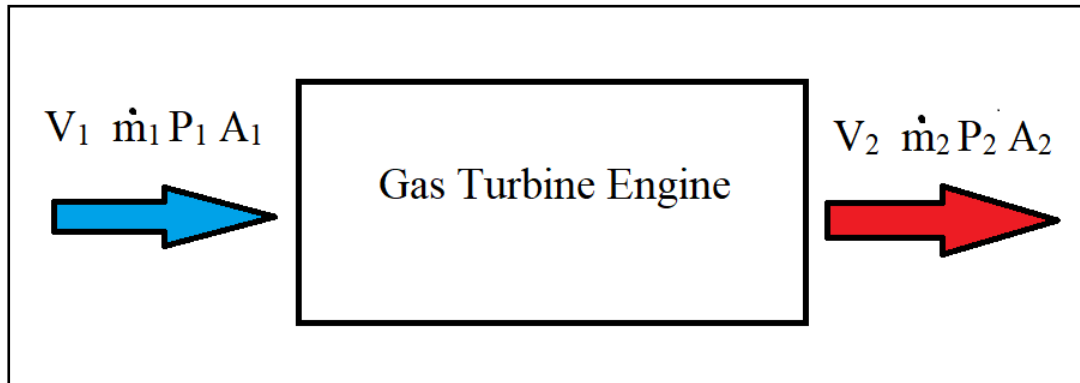


Figure 2.10: Basic Thrust Parameters.

The air entering the engine is compressed in the axial or radial compressor. The pressurized air is burned in the cannular or annular combustion chamber. The burnt air is sent to the turbine and the compressor is driven with the return obtained from the turbine. Even though they have different designs, all gas turbine engines work on the same principle. As can be seen when equation (2.3) is examined, there are two ways

to increase the thrust of the engine. One of these is to increase the difference in inlet and outlet air speed, and turbojet engines work on this principle. The other is to increase the mass of air passing through the engine, as turboprop engines do. As a result, engine thrust can be increased by increasing the speed, pressure or mass of the air drawn into the engine, but this increases the erosive effect of airborne particles on engine parts. One of the parts affected by erosion is the turbine blade. In this study, the relationship between turbine blade cooling holes and erosion damage will be examined.

2.4. Turbine Blades

Turbine blades have been one of the determining parts of engine life span since the 1930s, when gas turbine engines were first produced. A large amount of air compressed by the compressor is mixed with fuel in the patch chamber and burned. After combustion, the hot air passing through the HPT nozzle flows over the turbine blades and produces the power that drives the compressor. At this time, the temperature of the air may be $\cong 1500\text{ }^{\circ}\text{C}$ [16].

There are two different types of turbine blade designs. These are impulse turbine and reaction turbine given in **Figure 2.11** [17]. In impulse turbines, the flow is directed to the blades at high speed. There is no change between blade input and output areas. In reaction turbines, rotation is produced by accelerating the flow.

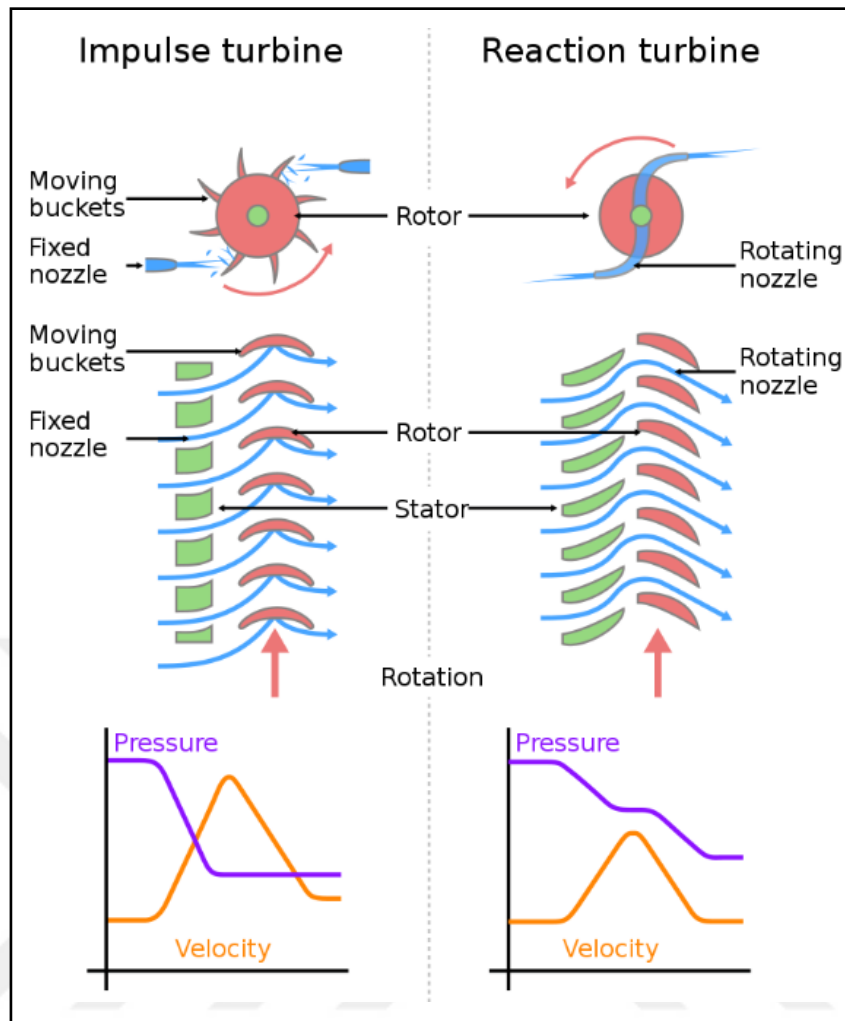


Figure 2.11: Impulse and Reaction Turbine.

In today's gas turbine engines, impulse-reaction turbines, which include the advantages of both turbine types, are used. The air coming out of the nozzle hits the blade, creating an impulse, and as it flows over the blade, it accelerates due to the narrowing area and creates a reaction. The resulting effect is transmitted to the compressor via the turbine disc and shaft via the turbine blade.

2.4.2. Function of HPT Blades Cooling Holes

While the turbine blades come into contact with hot air on their surfaces during operation, they are also cooled by cooling air from inside. While the cooling air used only passes through the blade in primitive gas turbine engines, in modern designs it is designed to form a film layer around the blade through holes drilled on the turbine. If the cooling air will only pass through the Turbin blades, it may be sufficient for the air to be at low pressure, but for effective cooling, a film layer must be formed, that is, the

air must be expelled from the cooling holes. In this type of cooling, the cooling air pressure must be higher than the external pressure of the turbine blades. The gas temperature in the turbine stages and the temperature reduced by the cooling effect on the blade surface can be seen in **Figure 2.12 [18]**.

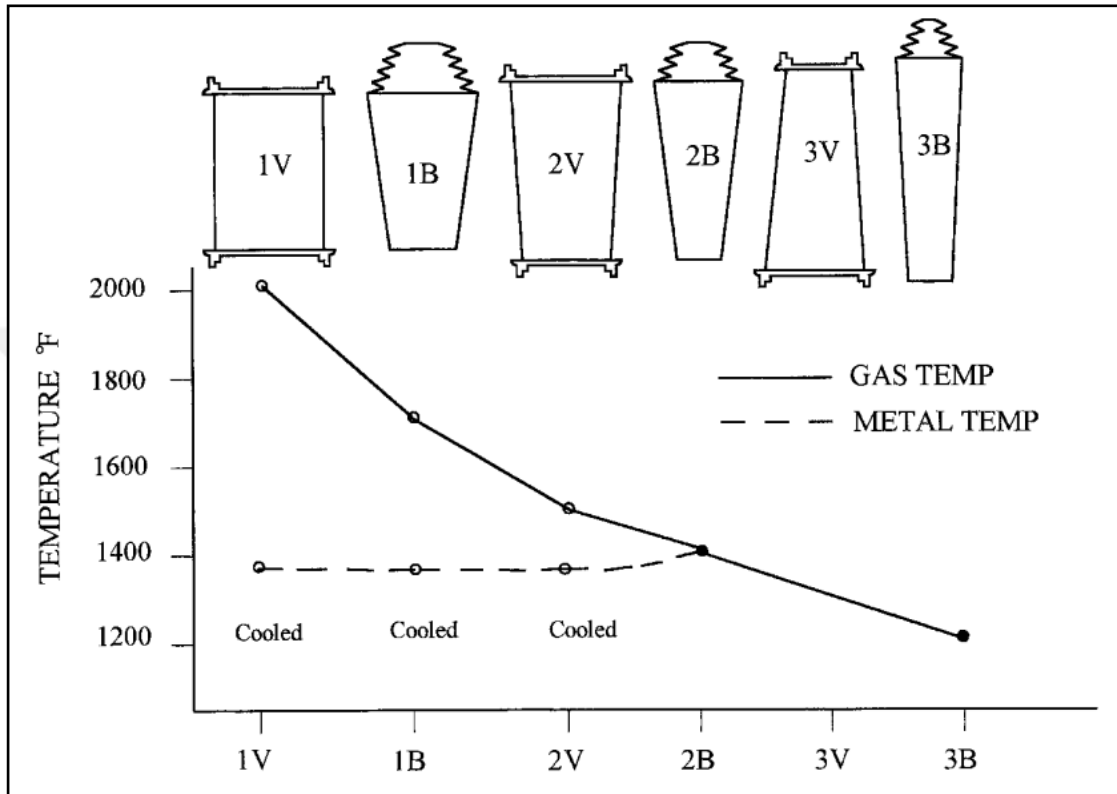


Figure 2.12: Turbine Vane and Blade Temperatures.

Developments in cooling techniques have played a critical role on the lifespan of turbine blades. It also enabled the engines to reach higher TIT turbine inlet temperature values. The development of cooling channels and holes is presented in **Figure 2.13 [19]**.

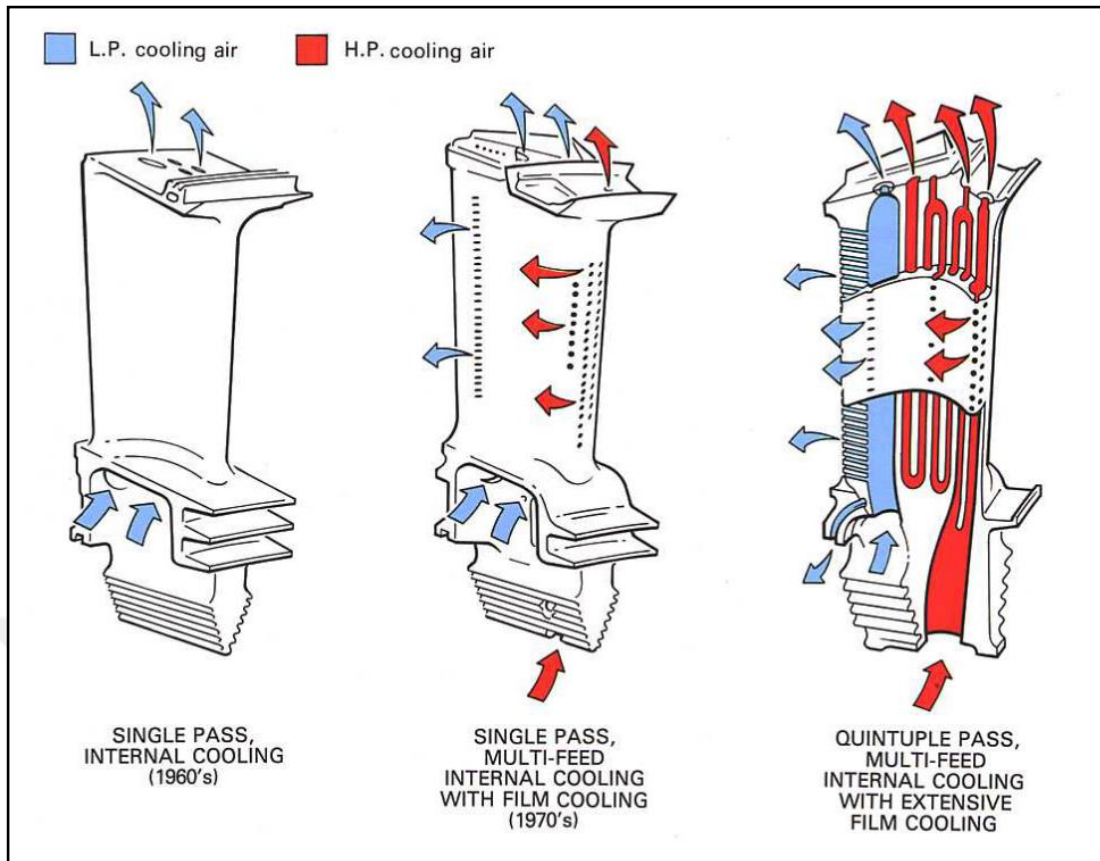


Figure 2. 13: Development of High-Pressure Turbine Blade Cooling.

Increasing TIT values over the years have enabled engines to operate more efficiently. The effect of increasing the turbine inlet temperature on specific output can be seen in **Figure 2.14** [20]. As can be clearly seen from the **Figure 2.14**, turbine inlet temperature increases cycle efficiency. Therefore, improving the high temperature resistance of turbine blades is of great importance. As can be seen in **Figure 2.15** [21], turbine inlet temperatures over 2200 F have been reached in current applications. This temperature is approximately equal to the melting temperatures of the superalloy materials from which turbine blades are produced. At these temperatures, it seems impossible for materials to maintain their strength without cooling with today's material technology. Cooling air enables the blades to operate at these temperatures.

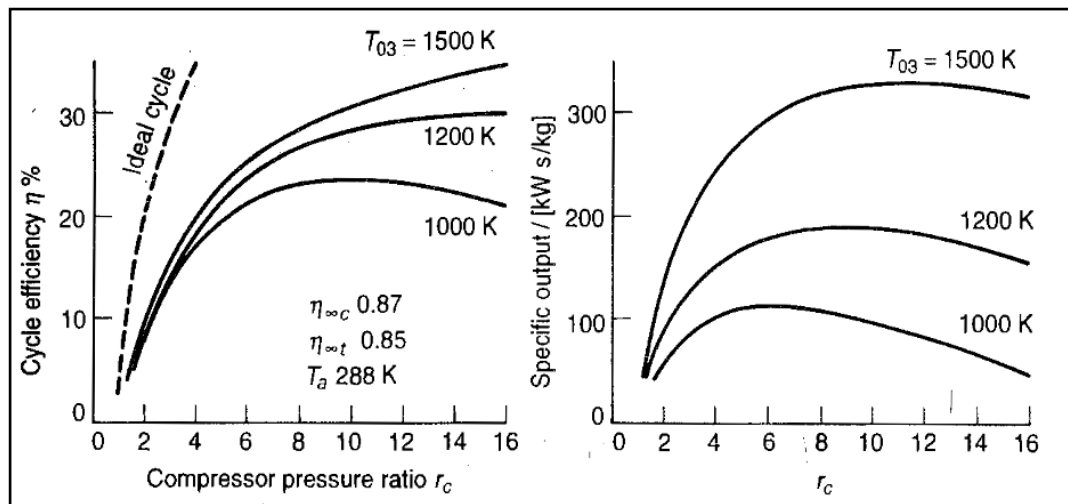


Figure 2.14: Cycle Efficiency and Turbine Inlet Temperature.

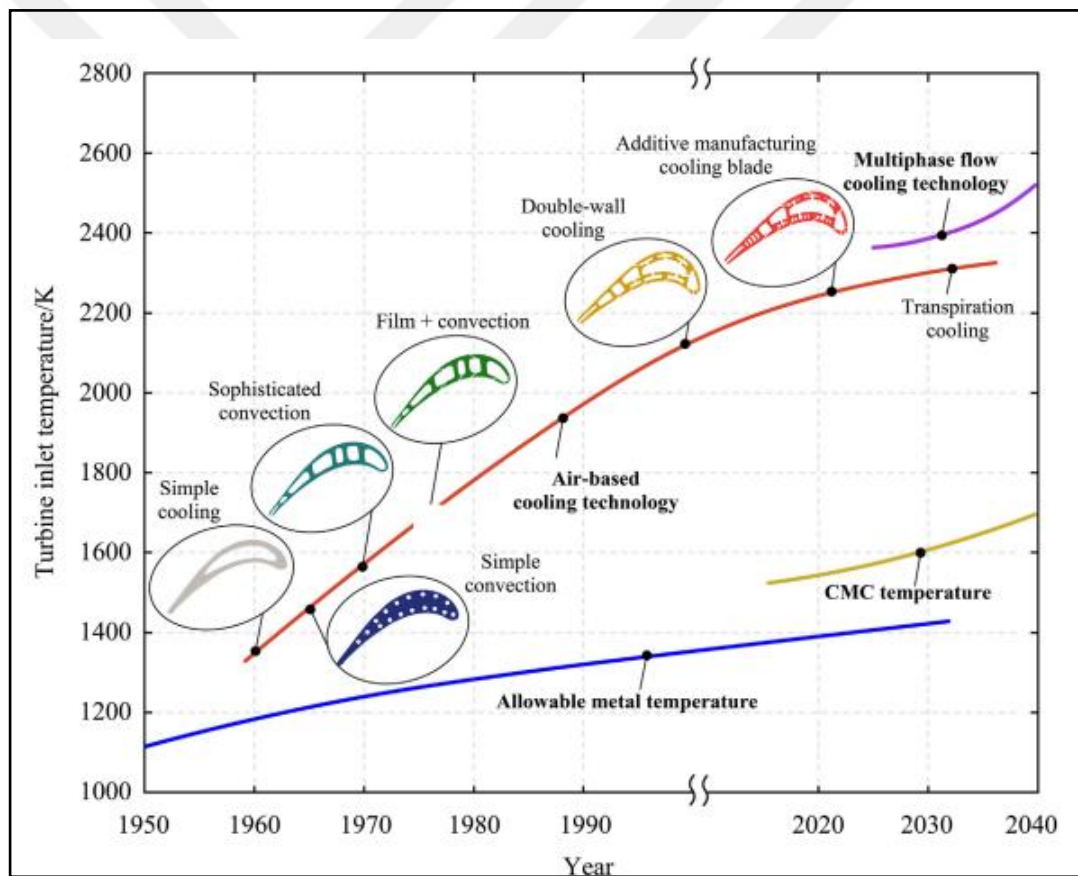


Figure 2.15: Cooling Systems Development.

2.5. Erosion

Erosion, which is a wear process, can be roughly defined as the removal of pieces from the surface by particles hitting the surface. This process is affected by a wide variety of factors such as the hardness of the part, impact angle speed, ambient temperature, material densities and particle shape [22,23,24]. Although numerical analyzes are also performed in order to have a prediction about erosion damage, they are frequently preferred in experimental methods due to the multitude of parameters affecting the process [25]. The amount of erosion is calculated as a dimensionless quantity obtained by dividing the amount of mass removed from the surface of the target part by the amount of abrasive particle mass.

$$W = \frac{\text{mass loss from surface material}}{\text{mass of impacting material}} \quad (2.4)$$

Particle impact angle, which is one of the most important variables in the erosion mechanism, has different effects depending on the hardness of the target metal. When the particle hits a hard metal, the amount of material it removes from the surface increases as the angle of impact increases. In the case of a ductile material, it lifts the most material at $\cong 30$ degrees. See **Figure 2.16**[23].

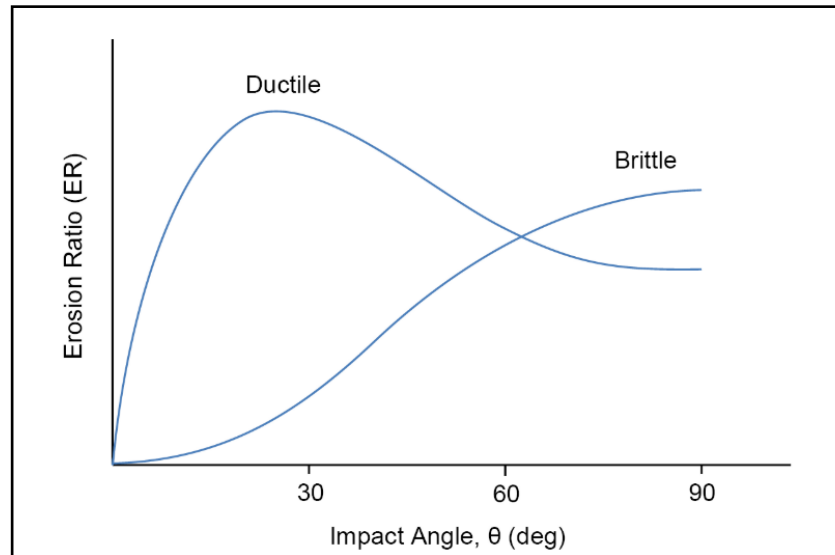


Figure 2.16: Erosion Rate Variation.

Another important erosion parameter, the impact angle, determines whether erosion damage will be in the form of cutting or scouring damage [24].

As the impact angle increases, the amount of scouring damage in erosion gradually increases. Damage types rate can be seen in **Figure 2.17** [26].

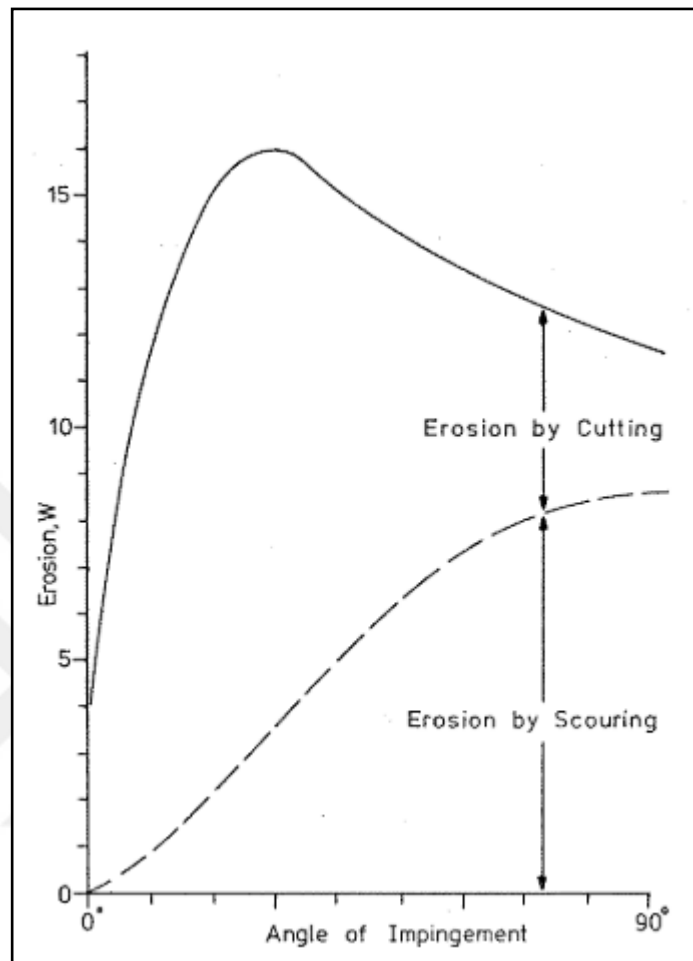


Figure 2.17: Types of Erosion Damage.

Although many mathematical methods have been developed to predict erosion damage, it is a type of damage that is difficult to predict, especially for engine parts used in aircraft that do not operate in a fixed location, as erosion varies depending on the characteristics of the impacting part, environmental conditions, the target part. Erosion wear has abrasive, shattering and corrosive effects and occurs in all additional types of gas turbine engines.

2.5.1. Erosion in Gas Turbine Engines

Gas turbine engines are machines that work with air and create a large amount of vacuum, which also makes them vulnerable to FOD. Due to their working principles, the air they breathe in often contains abrasive particles. Filtering the air causes

additional weight and efficiency losses. However, abrasive particles in the air seriously affect engine performance and life [27]. In addition, gas turbine engines used in aviation may have to operate in harsh environments such as deserts and volcanic terrain. Erosion caused by air drawn from dusty environments can reduce the efficiency of the engine and have catastrophic consequences. Erosion can occur due to dust drawn from the air intake, as well as rain, hail, ash and sea salt. At the same time, the fuel sprayed from fuel nozzles can also be a factor of erosion [28].

The parts of the gas turbine engine that are likely to be affected by erosion and the consequences of the effects are as follows.

LPC and HPC: Increased surface roughness due to material removal and deposits, fatigue cracks from erosion nicks. More erosion is seen in the root part of the radial compressors and the tip of the axial compressors.

Housing abradable coating: Increased tip clearance due to over-wear coating. The eroded coating creates erosive material for the next stages.

Rubber coating, labyrinth seals and spacer seals: Erosion, which can be seen on all sealing elements, may cause deterioration in air flow, loss of efficiency and additional loads on parts.

Variable and static vanes: Erosion can cause deterioration in vane geometry and increase in surface roughness. It may also adversely affect the movement of the variable vanes.

Injection system: The erosion of the injection nozzles causes the fuel flow to be disrupted, which can subsequently increase the temperature in the combustion chamber to undesirable levels.

Turbine system: At high temperatures, metals become more susceptible to solid particle erosion due to the combined erosion-corrosion effect [29]. Abrasions on the blade surface can affect the geometry of the cooling holes, reducing cooling efficiency. In addition, the cooling air holes are blocked in the erosive environment. Erosion can also occur due to molten particles. Molten particles can cause deposition in hot parts. They form an extremely fragile glassy layer during cooling when the engine is stopped. This type of erosion damage is mostly caused by volcanic ash.

In gas turbine engines, sealing is an important issue that is given much attention and directly affects engine performance. For this reason, sealing elements such as labyrinth seals, brush seals and abrasive coatings, which are intended to rub against the part against which the engine operates during operation, are frequently used. Changing dimensions of the engine due to both centrifugal and thermal effects may cause this friction to increase or decrease over time. When friction increases, the engine may produce erosive material within itself. In addition, when dust that causes erosion removes material from a surface, it also produces a new erosive material. On the other hand, some of the erosive materials lose their effectiveness to some extent due to the decrease in their hardness in the turbine stages. However, particles in the solid phase still have the energy to cause erosion [30].

The parts of a gas turbine engine that produce erosive material during operation are given below.

The gap between the rotor blade and the casing is of great importance in terms of engine efficiency and fuel consumption [31]. The region where abradable coating is used is shown in **Figure 2.18** [32]. In aviation applications, abradable coatings are frequently used on the casing in order to easily adjust the type clearance. The abradable coating has an important trade-off point that it is desired that the coating wears easily not to damage the blade tip and that it is strong enough to withstand the erosive material carried by the air flow [33]. The reason why these coatings wear easily is that they contain hard particles adhered to the soft filling material. At the micro level, the coatings are eroded by easily breaking the particles in question. As a result of the abrasion of these hard particles from the coating surface, they produce erosive material for the stages that follow them.

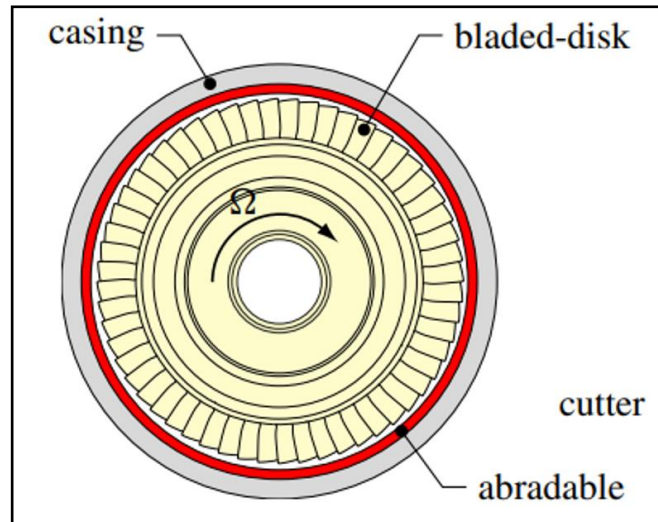


Figure 2.18: Abradable coating.

The protective coatings used on the fan or compressor blades can also wear out over time and produce with erosive material.

During the combustion process in the combustion chamber, soot and coke particles are also produced. Although they are apparently soft, they have an erosive effect on the hot part parts. Also, the deterioration of the fuel flow and the unburned fuel also cause the erosive effect.

The TBC (thermal barrier coating) coating on the hot parts wears off over time. Eroded particles are erosive for the back stages [34].

Labyrinth seals and honeycombs are frequently used in gas turbine engines as reciprocating seals. Labyrinth seals provide sealing by penetrating a little from the honeycomb surface. During this process, abrasive coating is applied to the tooth tips to prevent wear of the labyrinth seal teeth. These coatings are made of very hard materials, and they erode over time, mix with the air flow and create an erosive effect.

2.5.2. Molten Particle Erosion

Molten particle erosion is a type of erosion that occurs primarily from volcanic ash [35]. Such materials first deposition on the blade surface and form a glassy layer, which causes cracks to form due to expansion differences after the engine is stopped. This damage mechanism is shown in **Figure 2.19** [36].

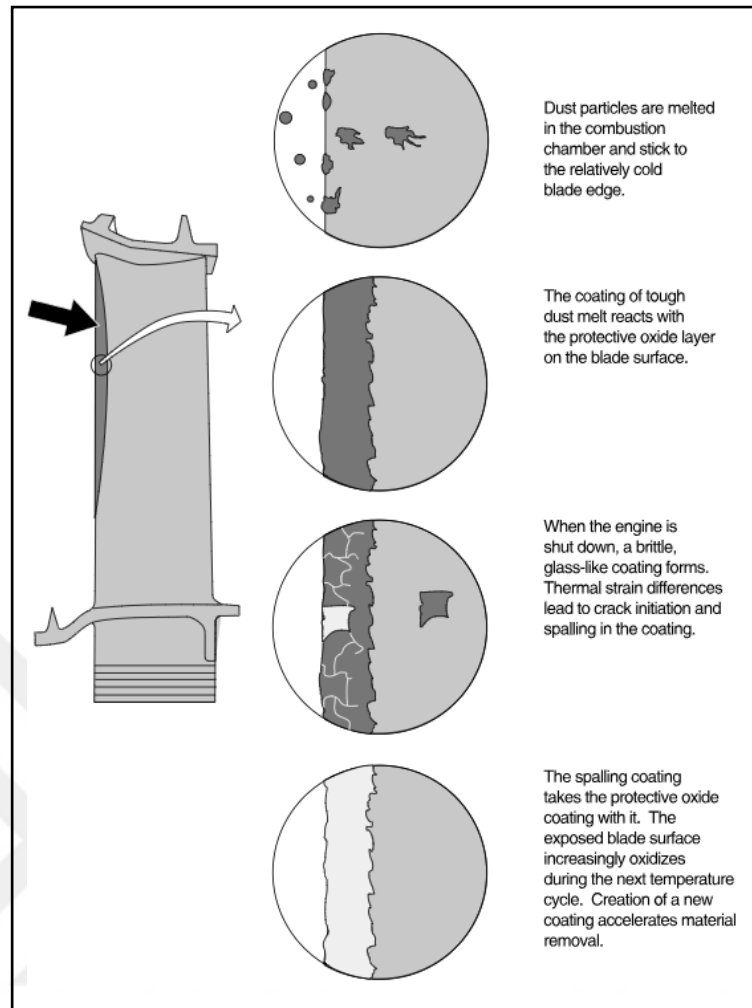


Figure 2.19: Molten Dust Particle Erosion Mechanism.

Briefly, the erosion of molten particles can be explained by first adhesion and then cracking of the glassy layer. In this study, we focused only on the effects of solid particles, ignoring the effects of molten particles.

2.5.3. Solid Particle Erosion

The erosion caused by solid particles can occur in various ways, depending on the particle energy and the properties of the part surface. Solid particle erosion can cause mechanical degradation, including the wearing of seals and bearings, and can change the shape and size of the blades, leading to lower working efficiency and worse performance [37]. Solid particle erosion is a factor that reduces flight safety and reliability [38].

Erosion caused by solid particles can occur in different ways, depending on the particle energy and the nature of the component surface. Hard particles cause abrasive removal

and introduce other harmful particles into the path, including tiny fragments of the engine material itself [38]. For ductile materials, microscale chip evacuation can be expected, while for hard and brittle materials, microscale fatigue processes may occur, leading to chipping and fracture. Brittle materials and coatings may spontaneously crack. Soot formed in the airflow during combustion can also cause severe corrosion of turbine blades [37].

TBC is usually the first to wear out due to erosion. The worn coating causes the thermal resistance of the blades to decrease. At the same time, the cooling holes on the blade may wear out and change shape, causing the cooling performance to decrease. Worn blades and stators also cause flow disruption and rotor vibration [39].

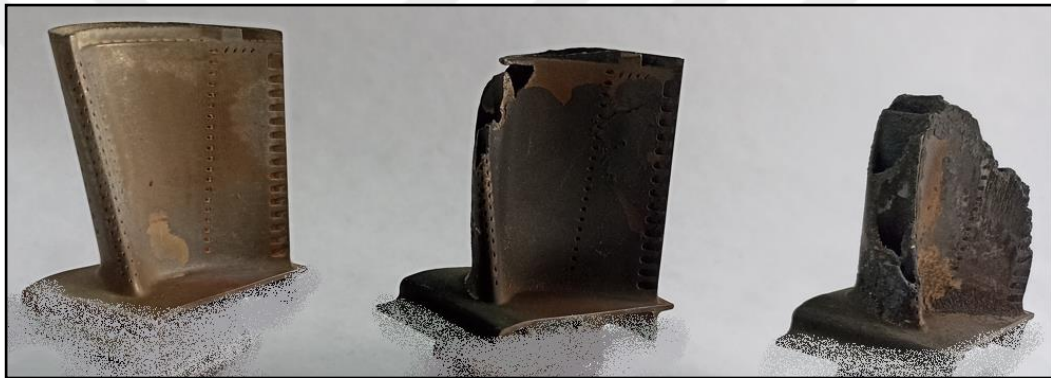


Figure 2.20: Examples of Erosion Damaged Blades.

3. EXPERIMENT

In this study, the relationship between blade cooling air and erosion damage was tried to be understood by changing various parameters on a sample turbine blade.

First of all, 220 grid aluminum powder was sprayed onto the blade at the angle at which the blade was exposed under operating conditions, without making any changes to an HPT blade that was already in use. During the sandblasting process, air was supplied at different pressures through the cooling holes at the root of the blade, thanks to the blade holder tool. The blade holder tool is presented in **Figure 3.1**.

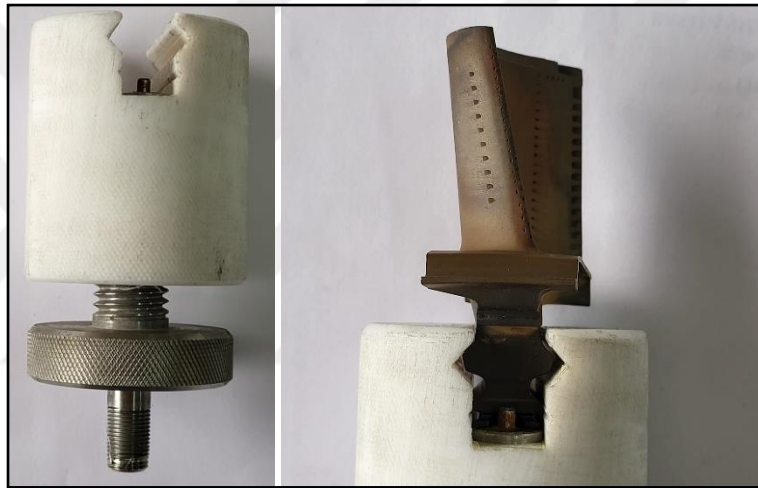


Figure 3.1: Blade Holder Tool.

In order to adjust the distance and angle between the blade and the sandblasting nozzle, a special tool is designed and produced as can be shown in **Figure 3.2**.

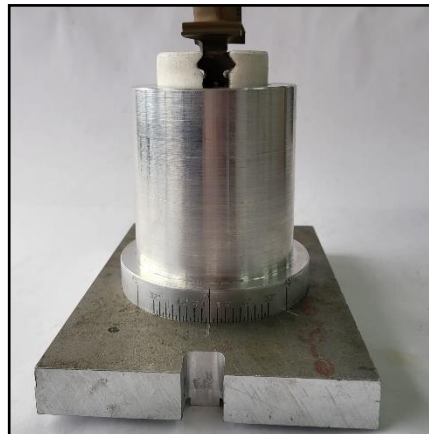


Figure 3.2: Distance and Angle Adjustment Tool.

The fixing kit, which brings together the distance adjustment set, blade holder set and nozzle holder set, is shown in **Figure 3.3** also presented.

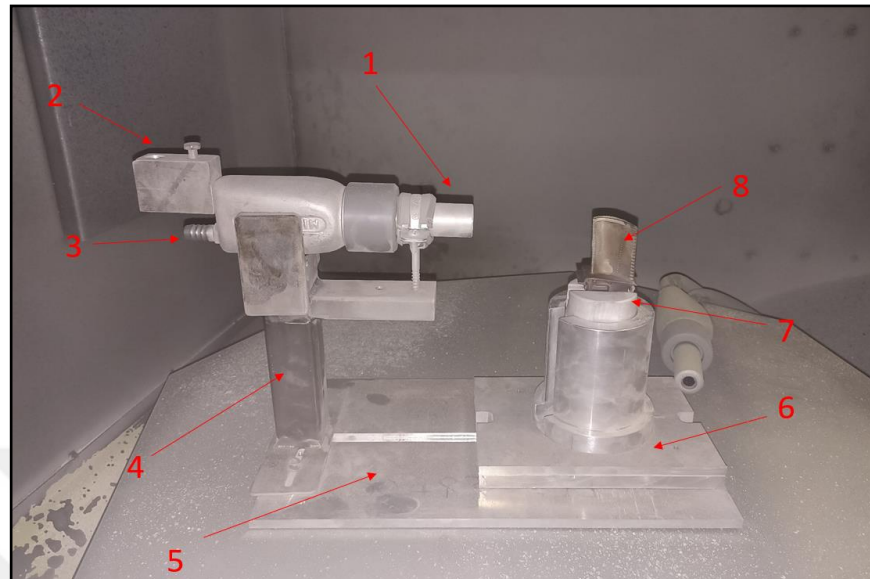


Figure 3.3: Fixing Kit.

Table 3.1: Fixing Kit.

Number	Part Name
1	Nozzle
2	Sand Inlet
3	Nozzle Air Inlet
4	Nozzle adjustment tool
5	Base Plate
6	Distance and Angle Adjustment Tool
7	Blade Holder Tool
8	Blade
9	Cooling Air Inlet

With the kit presented in **Table 3.1**, sandblasting operations were carried out in a sandblasting machine where nozzle pressure and secondary air pressure can be adjusted. The bench is shown in **Figure 3.4**.



Figure 3.4: Sandblasting Machine.

In order to examine the effect of the cooling hole angles, the angles of the cooling holes were intervened and the hole diameters were increased to 0.025 inches and the hole angles were changed to 45 and 90 degrees each. These operations were carried out on the EDM machine shown in **Figure 3.5**.

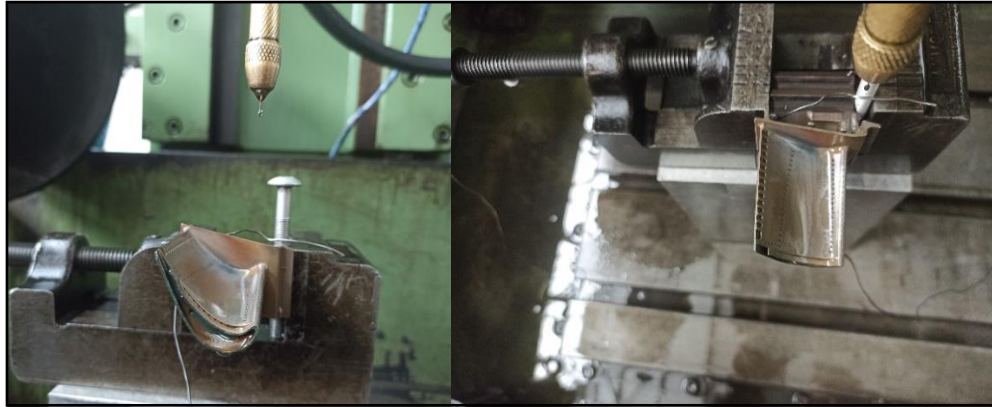


Figure 3.5: Electrical Discharge Machining.

The effect of temperature was not included in our study. The angle and distance between the blade and the nozzle were kept constant with the help of the tool used. In our experiment, the effect of cooling air on erosion was tried to be seen by changing the sandblasting pressure and cooling pressure. As output parameters, dimensional control was made on the pressure side and leading edges of the blades, which are most

eroded under usage conditions [3]. Precise weight measurement was made to observe the total weight change in the blade.

The input parameters and expected output parameters in our experiment set are presented in **Table 3.2**.

Table 3.2: Parameters.

Input Parameters	Output Parameters
Secondary Air Pressure	Leading Edge Erosion
Nozzle Pressure	Pressure Side Erosion
Cooling Hole Angle	Total Blade Weight

4. RESULTS

4.1. Zero Cooling Holes Effect

In our study, first, sandblasting was done on the original part from a distance of 50 mm at 20,40,60,80 PSI blasting pressure and 0,20,40,60,80 PSI cooling air pressure. 350 gr of aluminum oxide was used each time. It was repeated 8 times with the same blades, and the results were taken with precision weighing at the end of each step. The total weight change of the blades at the end of the experiment is shown in **Table 4.1**.

Table 4.1. Total Weight Change.

Cooling Gun	0 PSI	20 PSI	40 PSI	60 PSI	80 PSI
20 PSI	0,1411 gr	0,1705 gr	0,1605 gr	0,1591 gr	0,1241 gr
40 PSI	0,5103 gr	0,5296 gr	0,5310 gr	0,5365 gr	0,5090 gr
60 PSI	1,1614 gr	1,0523 gr	1,0918 gr	1,0813 gr	1,2133 gr
80 PSI	1,9328 gr	2,1418 gr	1,9191 gr	1,9678 gr	1,9716 gr

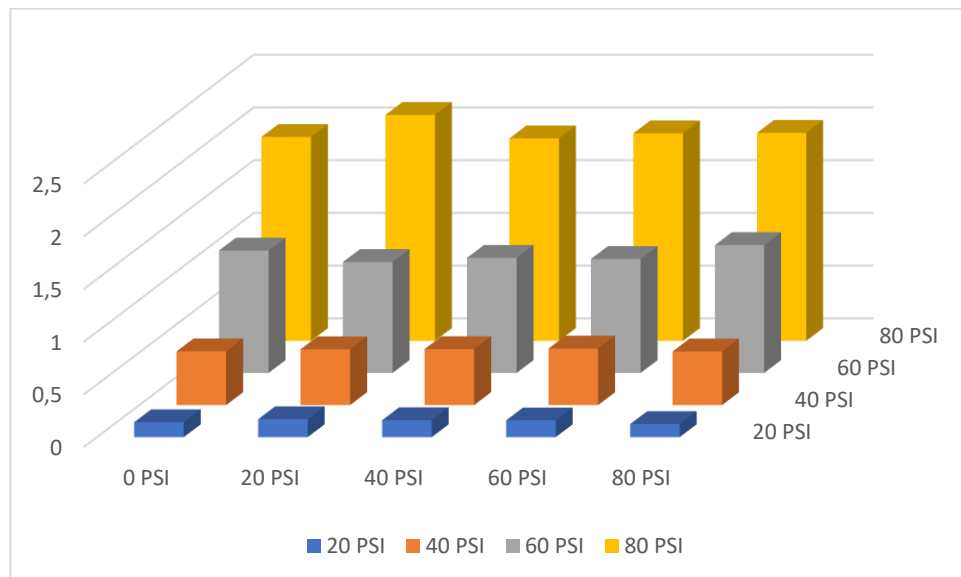


Figure 4.1: Total Weight Change.

As can be seen from the results, changing the cooling pressure in the original configuration did not have a significant effect on erosion.

As a result of this experiment it was concluded that the angle of the cooling holes on the blade is critical. It has been noticed that in order for the cooling air to be effective on erosion, the energy of the sand grains causing erosion must be reduced by changing the speed or angle. However, it has been understood that the current cooling flow adheres to the airfoil surfaces as much as possible to ensure ideal cooling, which provides good cooling but does not have an effect on reducing erosion.

4.2. 45 and 90 Degrees Cooling Hole Effect

The result obtained in the experiment with original cooling holes showed that the secondary air in their current state do not have a reducing effect on erosion.

It was evaluated that this situation was mainly caused by the holes being opened at as tangential angle as possible relative to the blade surface. Thereupon, it was decided to repeat the experiment after opening the holes at a wider angle in the same location to understand the effects of hole angles on erosion.

The new angles of the holes are given in **Figure 4.2**. By widening the angles of the holes, the objective is to attenuate the velocity of sand grains, thereby reducing erosion.

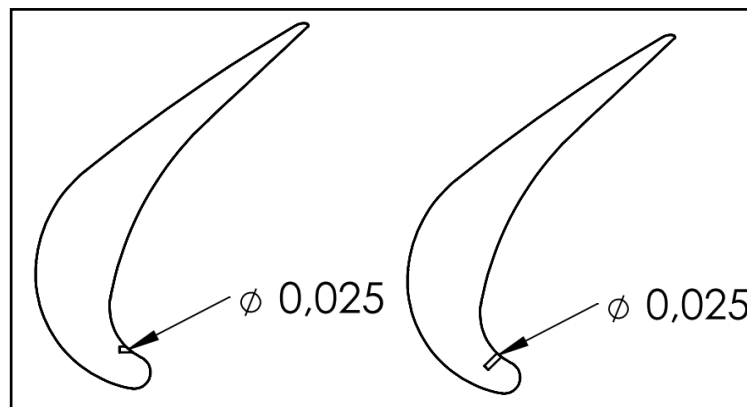


Figure 4.2: Blades with 45-degree (left) and 90-degree (right) holes.

The angles of the holes were changed using the EDM wire erosion method, without changing the location of the old holes, so that the hole diameters were 0.025 inches. As a result of the procedures, 3 blades were prepared before starting the experiment. One is completely original configuration. One with cooling holes 0.025 inches 45 degrees and the other with cooling holes 0.025 inches with 90 degrees.

All three blades were sandblasted with 220 grit 350 gr aluminum oxide from 50 mm with 90 PSI blasting pressure. 100 PSI secondary air was given from the root of all three blades.

At the end of the eighth blast, it was seen that the pressure side of the blade in the original configuration was punctured, and the other two blades were less damaged.

As a result of the experiment, the amount of erosion on the blades was determined by measuring with a precision scale. The weights obtained at the end of each sandblasting and the total weight reduction are presented in **Table 4.2**.

Table 4.2: Weight of Blades.

	original	45 degree	90 degree
0	149,5703 gr	150,2503 gr	151,7267 gr
1	149,3172 gr	150,0278 gr	151,5127 gr
2	149,0471 gr	149,7949 gr	151,2981 gr
3	148,8252 gr	149,5944 gr	151,1249 gr
4	148,6029 gr	149,4035 gr	150,9416 gr
5	148,3614 gr	149,1784 gr	150,7384 gr
6	148,1092 gr	148,9511 gr	150,5450 gr
7	147,9141 gr	148,8082 gr	150,4188 gr
8	147,7129 gr	148,6312 gr	150,2845 gr
Total	1,8574 gr	1,6191 gr	1,4422 gr

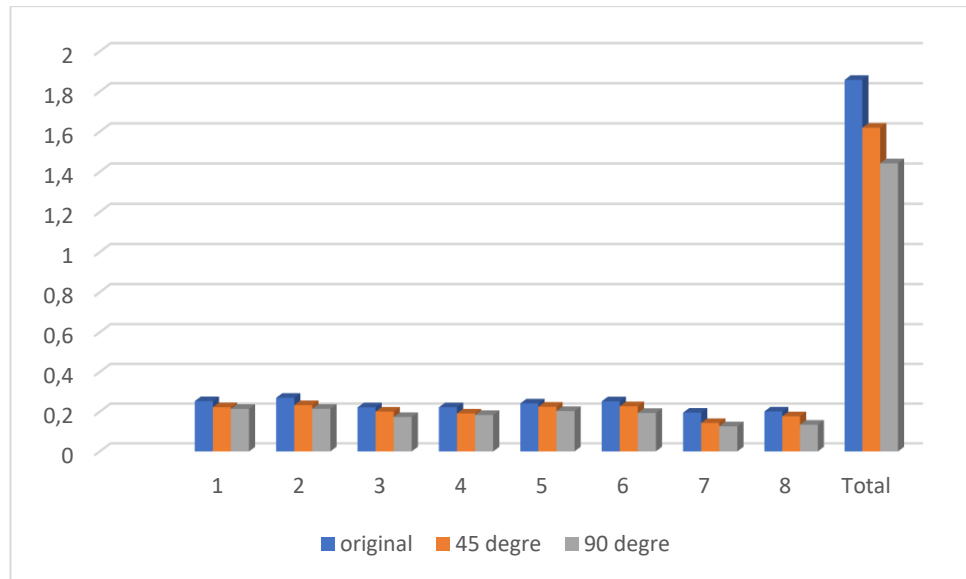


Figure 4.3: Weight Losses of Blades.

The experiment ended with the formation of a hole in the original blade pressure side. The damage is noticeably greater on the original blade. Additionally, the blade with 90-degree cooling holes suffered significantly less erosion damage than other blades.

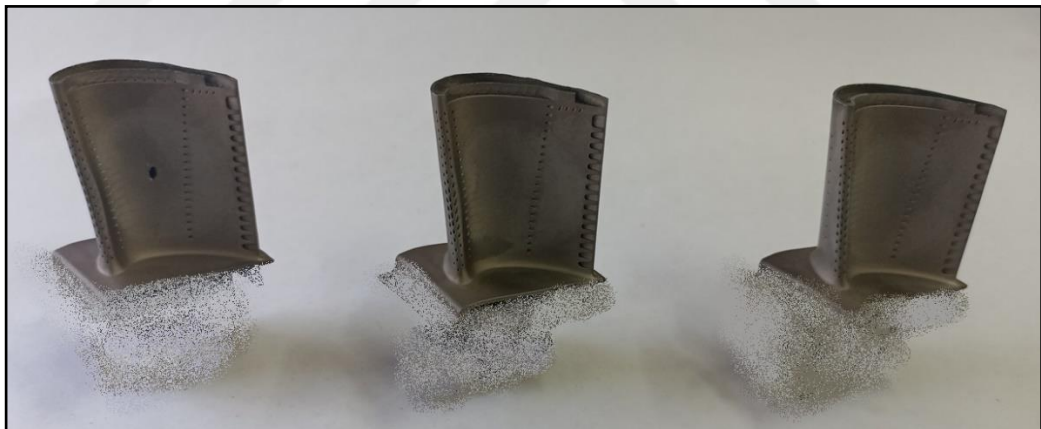


Figure 4.4: Blades With 0,45,90-Degree Cooling Holes.

In order to better understand the amount of damage, measurements were taken with an optical comparator device on the leading edges of the blades. In the original configuration, the depth of the most worn spot on the leading edge was measured as 0.762 mm, while the wear was 0.508 mm when the cooling holes were at 45 degrees and 0.381 mm with the cooling holes at 90 degrees.

Similarly, in the measurements made on the blade pressure side, the measure of the deepest point was 0.9956 mm in the original configuration, 0.8798 mm when the cooling holes were at 45 degrees, and 0.5816 mm when the cooling holes were at 90 degrees. The image obtained from the device screen is presented in **Figure 4.5**.

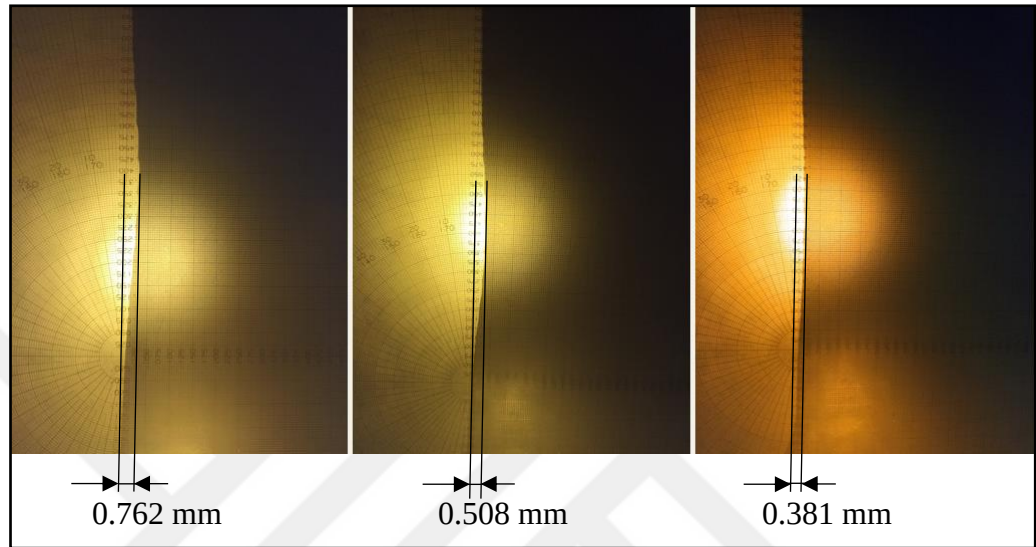


Figure 4.5: Optical Comparator images 0,45,90-degree cooling holes.

Examination under a stereo microscope showed that increasing the hole angles reduced the area exposed to erosion damage. The area screened by cooling air increased by increasing the angle of the holes. The image obtained with a stereo microscope at 16X magnification is presented in **Figure 4.6**.



Figure 4.6: Stereo Microscope Images 0,45,90-degree cooling holes.

5. CONCLUSION

Erosion is one of the critical factors that increases engine maintenance costs by shortening the engine maintenance interval [40]. It is an important problem, especially for engines used in aircraft performing take-off and landing missions on sandy terrain [3].

Our study showed a parallel distribution with studies conducted in previous years in terms of both particle trajectories and the erosion-reducing effect of secondary air flow [30,34,41]. The innovation in our study lies in the alteration of both hole diameters and angles, incorporating the utilization of secondary airflow to directly mitigate erosion. With the advancement of secondary air systems in recent years, it appears feasible to employ secondary air to mitigate erosion damage.

Our study consists of two steps. In the first stage of our study, the effect of cooling air pressure on erosion was examined by making changes only in the cooling air pressure without making any changes through the holes opened for cooling purposes. At this point, it has been observed that increasing the cooling air pressure does not have a significant effect on erosion with the current configuration of the cooling holes.

In the second stage of the study, the effects of cooling air on erosion were examined by modifying the cooling holes to different angles and widths. It has been shown that changing the angle of the holes significantly reduces erosion. At this point, it has been seen that erosion damage can be significantly reduced by making changes to the existing cooling holes.

However, excessive use of cooling air may cause loss of efficiency in the engine and may also have negative effects on the flow of cooling holes with changing angles. Therefore, a balance will need to be maintained between cooling effectiveness and erosion resistance. These effects were excluded from this study.

In terms of maximum benefit, it is important to find the most appropriate balance point by making flow and thermal calculations separately.

In addition, it is envisaged that erosion damage can be reduced by using secondary air not only on turbine blades but also on parts that are more exposed to erosion, such as the compressor rotor or stator parts.

6. FUTURE WORK

Although our study was conducted on turbine blades, erosion is an important problem for the engine as a whole, so the use of secondary air can be considered to prevent erosion in the fan and compressor parts.

When creating a new design or updating a configuration, the trade-off point should be taken into account, as in almost every design [41]. To prevent erosion of engine parts, it is necessary to consider how engine performance will be affected by the use of secondary air and perhaps consider a system such as an anti-icing that is only activated in dusty conditions.

Additionally, by taking into account thermal effects, a system that reduces erosion to be used on the engine can be developed. Our study has been useful in evaluating whether a phenomenon that seems theoretically possible will actually occur. In order to use this benefit in real life, the issue must be evaluated from the perspectives given in this thesis.

REFERENCES

- [1] Meher-Homji C. B., (1997), “The Development of the Junkers Jumo 004B: The World’s First Production Turbojet“, ASME 1996 International Gas Turbine and Aeroengine Congress and Exhibition, vol. 2.
- [2] Nagaiah N. R., Geiger C. D., (2014), “Evolutionary numerical simulation approach for design optimization of gas turbine blade cooling channels“, International Journal of Simulation and Multidisciplinary Design Optimization, 5(1), A22.
- [3] AGARD Conference Proceedings, (1994), "Erosion, Corrosion and Foreign Object Damage Effects In Gas Turbines", Neuilly-Sur-Seine, France.
- [4] Correa S. M., (1998), “Power generation and aero propulsion gas turbines: From combustion science to combustion technology“, Symposium on Combustion, 27(2), 1793–1807.
- [5] Boyce M. P., (2012), “Gas Turbine Engineering Handbook”, 4th Edition, Butterworth-Heinemann.
- [6] Vyncke-Wilson D., (2013), “Advantages of aero-derivative gas turbines in industrial applications: Technical, operational, and financial considerations on equipment selection“, 20th Symposium on Industrial Applications of Gas Turbines Committee, pp. 1–15.
- [7] Farokhi S., (2014), “Aircraft Propulsion” 2nd Edition, John Wiley & Sons Ltd.
- [8] Leishman G., (2022), “Introduction to Aerospace Flight Vehicles” 1st Edition Embry-Riddle Aeronautical University.
- [9] Bintaş M., (1992), “J79-19 Turbojet Motorunun Performans Degerlendirmesi Ve Hava Giriş Süzgecinin Tepki Kuvvetine Olan Etkisi”, Master's Thesis Anadolu University.
- [10] Zaharia S. M., (2016), “Reliability based inspection techniques of turbojet engine compressor blades“, Mechanical Testing and Diagnosis, vol. 2, pp. 15-24.
- [11] Pashilkar A. A., Lathasree B., (2011), “Digital simulation model for a turboprop engine“, Symposium on Applied Aerodynamics and Design of Aerospace Vehicle, pp. 16-18.
- [12] Gu N., Wang X., Lin, F. (2019), “Design of disturbance extended state observer (D-ESO)-based constrained full-state model predictive controller for the integrated turbo-shaft engine/rotor system“, Energies, 12 pp. 1–24.
- [13] Litt J., Wong E., Krasowski M. J., Greer L.C. (2003), “Cooperative Multi-Agent Mobile Sensor Platforms for Jet Engine Inspection Concept and Implementation” International Conference on Integration of Knowledge Intensive Multi-Agent Systems, NASA/TM—2003-212708.

- [14] Stureson P. (2018), “Sense, Actuate and Survive: Ceramic Microsystems for High-Temperature Aerospace Applications”, Doctoral Thesis Uppsala University.
- [15] Alves P., Silvestre M., Gamboa P. (2020), “Aircraft Propellers—Is there a future?”, *Energies*, 13(6), 1–17.
- [16] Spittle P. (2003), “Gas turbine technology“, *Physics Education*, 38(6), 504–511.
- [17] Wikipedia, (2023), <https://en.wikipedia.org/wiki/Turbine>. Date of Access: 08.02.2023.
- [18] Giampaolo T. (1959), “Gas Turbine Engine Handbook”, 3rd Edition the Fairmont Press, Inc.
- [19] Han P. (2017), “Additive Design and Manufacturing of Jet Engine Parts“, *Engineering*, 3(5), 648–652.
- [20] Saravanamuttoo H. I. H., Rogers G. F. C., Cohen H., (2013), “Gas Turbine Theory”, 5th Edition, Pearson.
- [21] Unnikrishnan U., Yang V. (2022), “A review of cooling technologies for high-temperature rotating components in gas turbine“, *Propulsion and Power Research*, 11(3).
- [22] Zhang N., Yang F., Li L., Shen C., Castro J., Lee L. J., (2013), “Thickness effect on particle erosion resistance of thermoplastic polyurethane coating on steel substrate“, *Wear*, 303(1–2), 49–55.
- [23] Hassani S., Bielawski M., Beres W., Martinu L., Balazinski M. Klemberg-Sapieha J. E. (2008), “Predictive tools for the design of erosion resistant coatings“, *Surface and Coatings Technology*, 203(3–4), 204–210.
- [24] Yildirim B., Müftü S. (2012), “Simulation and analysis of the impact of micron-scale particles onto a rough surface“, *International Journal of Solids and Structures*, 49(11–12), 1375–1386.
- [25] Hamed A. (1989), “Influence of Secondary Flow on Turbine Erosion“, *Journal of Turbomachinery*, 111(3), 310–314.
- [26] Tilly G. P., Sage W. (1970), “The interaction of particle and material behavior in erosion processes“, *Wear*, 16(6), 447–465.
- [27] Szczepankowski A., Szymczak J., Przysowa R. (2017), “The Effect of a Dusty Environment upon Performance and Operating Parameters of Aircraft Gas Turbine Engines“, *Impact Volcan. Ash Clouds Mil. Oper.*, pp. 1–13.
- [28] <https://aeroenginesafety.tugraz.at/doku.php?id=5:53:531:531>. Date of Access: 14.02.2023.

- [29] Bonu V. Barshilia H. C., (2022), “High-Temperature Solid Particle Erosion of Aerospace Components: Its Mitigation Using Advanced Nanostructured Coating Technologies “, *Coatings*, 12(12).
- [30] Hamed A., Tabakoff W., Wenglarz R., (2006), “Erosion and deposition in turbomachinery“, *Journal of Propulsion and Power*, 22(2), 350–360.
- [31] DeMasi-Marcin J. T., Gupta D. K., (1994), “Protective coatings in the gas turbine engine“, *Surface and Coatings Technology*, 68–69(C), 1–9.
- [32] Salvat N., Batailly A., Legrand M., (2013), “Modeling of abradable coating removal in aircraft engines through delay differential equations“, *Journal of Engineering for Gas Turbines and Power*, 135(10).
- [33] Maozhong Y., Baiyun H., Jiawen H., (2002), “Erosion wear behavior and model of abradable seal coating “, *Wear*, 252(1–2), 9–15.
- [34] Swar R., Hamed A., Shin D., Woggon N., Miller R., (2012), “Deterioration of thermal barrier coated turbine blades by erosion“, *International Journal of Rotating Machinery*. Volume 2012, Article ID 601837, 10 pages.
- [35] Pearson D., Brooker R., (2020), “The accumulation of molten volcanic ash in jet engines; simulating the role of magma composition, ash particle size and thermal barrier coatings“, *Journal of Volcanology and Geothermal Research*, 389, 106707.
- [36] <https://aeroenginesafety.tugraz.at/lib/exe/detail.php?id=5%3A53%3A532%3A532&media=5:53:532:dust-particle-melting.svg>. Date of Access: 17.11.2023.
- [37] Alqallaf J., Ali N., Teixeira J. A., Addali A., (2020), “Solid particle erosion behavior and protective coatings for gas turbine compressor blades-A review“, *Processes*, 8(8).
- [38] Zhang J., Liu H., (2023), “Effect of solid particles on performance and erosion characteristics of a high-pressure turbine“, *Energy*, 272, 127185.
- [39] Nomoto H., (2017), “Solid particle erosion analysis and protection design for steam turbines“, *Advances in Steam Turbines and Modern Power Plants*, pp. 219–239.
- [40] Olzak B., Szymczak J., Szczepankowski A., (2007), “Gaseous erosion and corrosion of turbines“, *Journal of the Polish CIMAC*, 199–204.
- [41] El-Sayed, A. F. A. A., Brown A., (1987), “Computer Predictions of Erosion Damage in Gas Turbines“, *American Society of Mechanical Engineers*, pp. 1-6.

BIOGRAPHY

The author started his career in 2014 as a gas turbine engine maintenance engineer. He has been working as an engine system engineer since 2019.

