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FABRICATION OF TURBOJET ENGINE

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ABSTRACT

The development of small jet propulsion systems has been a recent endeavor, despite the long history of gas turbine research. Advancements in this field pose significant challenges, demanding meticulous attention to detail for enhancing overall performance. Traditionally used in model jet engines, these small engines are now being adapted for integration into Unmanned Aerial Vehicles (UAVs). This dissertation focuses on developing a small-scale turbojet, utilizing components from the IHI RHB31 VZ21 model turbo. The design process involved studying various turbojet components and thermodynamic cycles, followed by dimensioning based on a scale factor derived from compressor diameters. SolidWorks software facilitated the design process, but fabrication challenges arose, particularly with extremely small components like the diffuser and compressor shroud. Despite efforts to adapt manufacturing techniques, achieving the desired quality proved difficult, hindering the fulfillment of key objectives.

Keywords: Radiometric Dating, Isochrons.

I. INTRODUCTION

The introduction section presents a general overview of the turbojet engine and its importance in the aviation industry. A turbojet engine can simply be defined as a type of gas turbine engine. The name "turbojet" is derived from the Latin name "turbo", meaning "spinning top" and "jet", a stream of air. Turbojet engines were the first type of jet engines to be developed and were essential in propelling early jet aircraft such as fighter planes and jetliners. They are also used on some medium-range missiles. The development of the turbojet engine is an important achievement in the aviation industry as it has drastically changed technology and influenced the modern era of transportation. Engineers and professionals in this field need to understand the basic concept of turbojet engines and their applications so that they can be developed to another level which may help in future progress. Turbojet engines have been mainly used in aircraft, both military and civil. The air which is drawn in at the front by the compressor is used to carry the fuel and then burn the fuel. A high gas exhaust velocity is obtained by increasing the temperature of the gas and by reducing the pressure from the intake to the exhaust end. It is hoped that this study about the turbojet engine will give a better understanding to the readers, especially about the principle and the applications that currently have been used in the aviation industry. The next section will discuss in detail how the design and development have been made from the basic principle of the turbojet engine to its real applications in the aircraft.

1.1. Overview of Turbojet Engines

Turbojet engines operate on the principle of sucking in air at the front of the engine using a rotating compressor. This air is mixed with fuel, and the mixture is burned. The hot exhaust gases provide forward thrust and turn the turbines which drive the compressor. The basic construction of a turbojet engine includes four main design features. These are the diffuser, the combustion chamber, the turbine, and the nozzle. The diffuser decelerates the air and increases pressure as it enters the engine. The combustion chamber is where the air is mixed with fuel and burned. The turbine extracts the energy from the hot gases leaving the combustion chamber and uses it to drive the compressor. Finally, the nozzle provides a path for the expanding gases to provide forward thrust. Every component in a turbojet engine has its own purpose and design considerations, and the engine has to be designed and built to withstand the forces of thrust and vibration and extremes of temperature. However, a turbojet engine by itself will not produce enough thrust to move a large aircraft from a standstill and it would be instantly swallowed up by an enormous amount of air. So an aircraft using a turbojet engine needs to open up the airflow to the engine by moving. At the same time, the engine has to be designed so that it is efficient at the high speeds that the aircraft will reach in flight. As a result, turbojet engines are ideally suited to fighters and other high-speed aircraft where once the aircraft is moving, the design of the engine can give maximum benefits. Overall, the turbojet engine is an engineering marvel that has revolutionized the transport and aviation industry and has many applications in modern times.

1.2. Importance of Turbojet Engines in Aviation

The turbojet engines are the most important type of jet engine used in the aviation industry. They are much more advanced in technology, and that's why they have replaced all other kinds of jet engines. These are the most powerful aircraft engines. Because of the power and the little bit of time it takes to get the full thrust after accelerating, turbojet engines are used in military airplanes and some other high-speed airplanes. The replacement of propeller engines with turbojet engines has greatly increased the speed of the aircraft. The greatest advance in aviation propelled by gas turbine engines may be to use a different type of engine for cruising flight and for takeoff and climbing. A large turbojet engine is most efficient in the high-speed range, so it is used in cruising. For takeoff and climb to a high altitude, a smaller turbojet engine is less efficient but produces greater thrust per pound of engine weight. So progress in the development of lighter gas turbine engines means that it may soon be practical to use two different gas turbine engines in commercial and military airplanes. These gas turbine engines, sometimes called turbofan engines, have a large turbojet engine with a fan mounted ahead of it. These kinds of engines take in more air than a regular turbojet engine. The fan moves a large amount of air around the smaller engine. Now more and more aircraft have been designed with turbofan engines because it is easier than a turbojet engine to make the transition from one type of engine to a new kind of engine. So the advantages of the turbojet engine compared to other types of power plants are small size, lightweight, high power, high speed, and low cost. However, there are disadvantages too. A great amount of noise is the major disadvantage of the turbojet engine, and the exhaust gases of the turbojet engine have very high velocity. They pose a danger if something comes into the engine and the air or the ground is located at the rear of the engine. The fuel efficiency of the turbojet engine is very low when the aircraft is flying with less than full thrust. More importantly, the fuel efficiency of the turbojet engine is about 20 times lower when the aircraft is flying at 60 percent.

II. METHODOLOGY

This chapter points out how the design and manufacturing process of each component of the mini-turbo jet was carried through. It is designed for each component of the engine, explaining how the dimensions were obtained for the design and, what are the materials for each component. The second section describes the manufacturing process chosen. A flowchart of methodology is presented in Figure 1.9, found at the end of this chapter.

DIMENSIONING PROCESS

2.1 COMPRESSOR

The starting point for the dimensioning of this engine is the compressor. The compressor chosen for this experimental project is from the turbo company IHI, the RHB31 VZ21 model.

From the literature examination, the compressors used in similar projects, for instance, Kamps's turbojet or the WPI turbojet, were centrifugal to offer a greater compression ratio and efficiency. Moreover, the turbo or the compressor/turbine set is easily available online and can be purchased at a relatively low cost, when compared to other turbos. Since it was already purchased, this compressor was used to develop this thesis.

The design of the compressor should be done with the exact measures, for the design to be accurate. To do so, the turbo producers were contacted. Nevertheless, it was not possible, for them, to give these dimensions as it is confidential information. The information through research for the compressor map, was found in the ECOTRON technical specifications document.

The basic dimensions, base thickness, impeller/blade height, and, impeller inlet/exit diameter were measured by the use of a caliper. Nonetheless, only the impeller exit diameter was needed.

According to Kamps, a model of a turbojet can be produced using his turbojet dimensions with a scale factor, achieved from a ratio between the compressor diameter, 36.6 millimeters, the Kamps's compressor diameter, 66 millimeters with a value of, approximately, 0.55. From this value, it was obtained the estimated dimensions of the engine pieces.

2.2 INLET

This piece is the cover of the engine at the compressor side that fixes the diffuser to the outer casing. It was designed based on the Worcester Polytechnic Institute project, adapting its size according to the compressor shroud and outer casing dimensions of this engine, for the design to fit in the outer casing with a very small clearance. In addition, the bolt holes were made to be in line with the diffuser and the outer casing holes, for a better coupling of both components.

Aluminum was the material opted for the manufacture of this component. However, it is not possible to specify the type of metal, owing to the fact this material was taken from a spare engine block.

2.3 DIFFUSER

The trickier and more challenging piece to design was the diffuser. The first step to take was choosing the diffuser style: bladeless or bladed, and, if it is bladed, decide between straight, forward-curved, or wedge-shaped blades. From the examples observed from the The trickier and more challenging piece to design was the diffuser. The first step to take was choosing the diffuser style: bladeless or bladed, and, if it is bladed, decide between straight, forward-curved, or wedge-shaped blades. From the examples observed from the literature, it was opted to design a wedge-shaped blade diffuser taking into consideration the fixing bolts, that allows the compressor shroud to cling to the diffuser and avoid leaks of the gas flow.

First, the diffuser was dimensioned dependent on the Kamps's diffuser. Thomas Kamps's book indicates the diffuser dimensions and includes the axial blade profile, displayed in figures 1 and 2

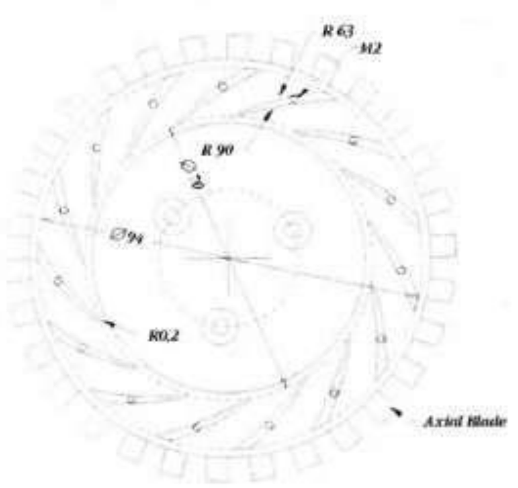

Figure 1: Diffuser

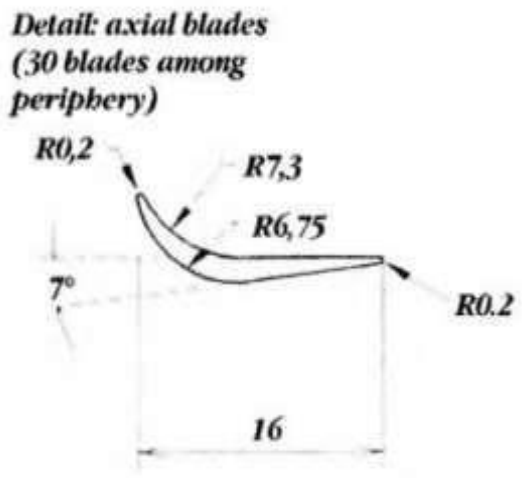

Figure 2: Diffuser Blading Profile

2.4 SHAFT AND SHAFT HOUSING

Reviewing mini-turbojets shaft designs such as the KJ66, AMT Olympus, or the Kamps's engine, it was observed that the designs were, relatively, equal. Therefore, the was dimensioned the shaft by scaling down the dimensions of Kamps's shaft described in Figure 3.

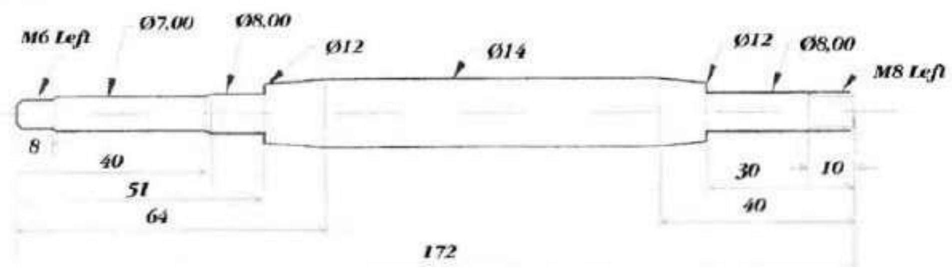

Figure 3: Shaft

The shaft accommodates two bearings, located at the bearing seats, positioning the bearing on both sides of the shaft. The steps are for tight-fitting of the bearings to prevent it from displacing. To produce this shaft, a stainless steel rod was decided as the material to be further machined.

The shaft housing was designed, like the shaft, to hold inside the shaft with the two bearings and, couple the diffuser, fixed with bolts to the housing, together with the stator housing, which will also be fixed with bolts to the housing. Despite the variety of shaft housing designs, the determined design would be simple and straight, widening at both ends of the housing to allow room for the bolts to fix the diffuser and stator housing. The

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dimensioning was executed by adapting to our scale the shaft housing dimensions that are represented in Figure 5.

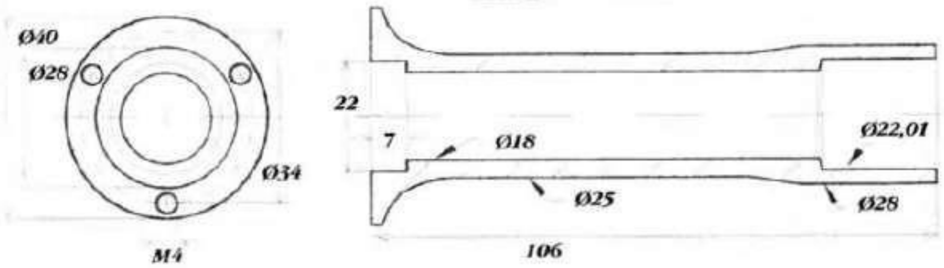

Figure 4: Shaft Housing

Aluminum is the material of which is constitutes the shaft housing, but its type is not feasible to determine since it was withdrawn from a spare engine block.

2.5 COMBUSTION CHAMBER

The design for the combustion chamber that was considered to be optimal, was an annular chamber. In consonance with the literature reviewed, it seemed the best choice for its simple design and practicality, in other words, it would facilitate the manufacturing process as opposed to the other types. Moreover, the combustor design, generally, comes from empirical data and, since the objective is not to improve a design, the choice of a combustion chamber, that had successfully performed its role, was the wisest choice to make. Therefore, it was decided to design it based on the combustion chamber of Kamps, adapting its size and holes for this combustion chamber. Consists of a stainless steel sheet of 0.5 mm width shaped into a tube with the desired diameter and a series of holes of different diameters. Figures 5 and 6 below demonstrate the combustion chamber design that was relied on. The combustion chamber has two tubes, one smaller tube, that goes inside the larger one. The hole's diameters and the distance between holes were scaled down to an adequate size and distance, concerning this mini-turbojet.

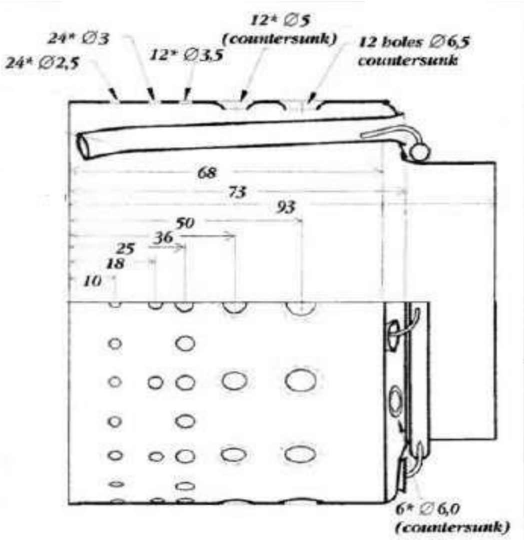

Figure 5: Outer Flame Tube

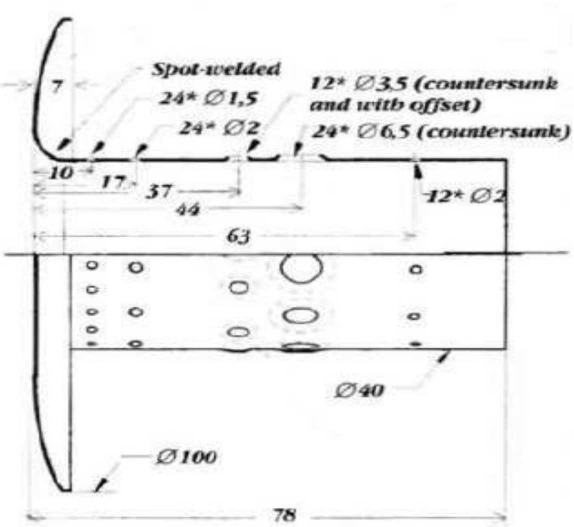

Figure 6: Inner Flame Tube

2.6 FUEL INLET

The fuel distributor, as the name states, disperses the fuel to the vaporization tubes of the combustion chamber. From the small gas turbines seen, the design is, almost, the same. Therefore, an injector ring was designed, with an adequate diameter, for the combustion chamber designed. The injector ring is set on the inner side of the combustion chamber of the turbine side, and, has various injectors corresponding to each vaporization tube. The fuel comes from an external source that is connected to a tube that crosses the outer casing to the combustion chamber, where it is also linked to the injector ring. The fuel distributor is made of a stainless steel tube with 3 millimeters of diameter

2.7 TURBINE

The turbine, like the compressor, was retrieved from the RHB31 VZ21 turbo.

2.8 EXHAUST NOZZLE

This component is responsible for the generation of thrust. Although, this dissertation does not have as a primary objective the optimization of the generated thrust, instead the design and manufacturing of a self-reliant small gas turbine. The nozzle design is a simple, convergent nozzle guaranteeing a straightforward construction that is designed from the dimensioning of this component, which was based on the literature review.

Figure 7, demonstrates the exhaust nozzle dimensions, although, it was scaled down and adapted to this jet engine. The recommended material for this component is a stainless-steel sheet of 0.5 millimeters thickness.

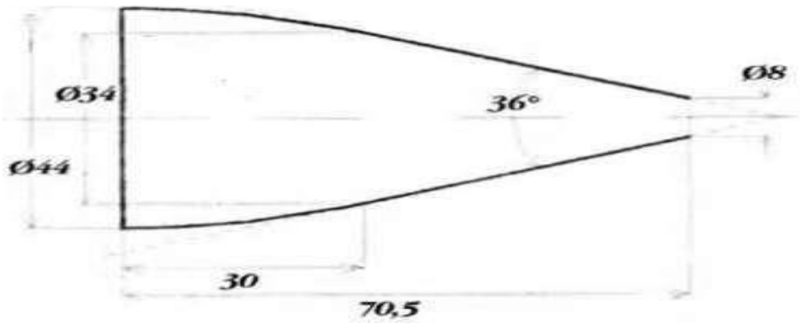

Figure 7: Exhaust Nozzle

2.9 OUTER CASING

The final part of this engine consists of a stainless-steel tube with 0.5 millimeters of thickness. At the compressor side, some holes were made to enable the bolts to pass through the casing, reaching the diffuser. The bolts were screwed, fixing the outer casing with the diffuser. At the other end, the outer casing is fixed to the nozzle guide vanes.

The design of this component, since it was one of the last to be designed, there was no need for scaling it down based on the literature. Having the other components designed, the outer casing has to cover, adequately, the gas generator.

MANUFACTURING PROCESS

The construction guidelines for this thesis, based on the literature reviewed and online videos of the model jet engine manufacture, are divided into two subsections, distinguished by the two main materials used to produce the needed components for the engine. One is aluminum and the second is stainless steel.

The aluminum-based components are the inlet flange, compressor shroud, and the diffuser. The production of these parts was made, with the help of UBI's FABLAB, Fabrication Laboratory, in the 5-axis CNC milling machine. It was considered to do it there due to the precision of the pro- duction, which is impossible to equalize if it was handmade, through the use of manual milling machines. For the 5-axis CNC milling machine to produce the desired component, it is required a .stp format file obtained from the design software, in this case, SOLIDWORKS software, saving options. With this procedure, round blocks of aluminum, are transformed into the expected shape, with an extremely low margin of operating error. However, the shaft housing was created through the manual operation of a lathe machine.

The stainless steel elements were manufactured with the use of a vertical drilling machine, a lathe machine, a roller, and a water jet machine. It was firstly used the water jet machine to cut the pieces designed for each component. The pieces were cut from a stainless steel sheet, consequently, the designed components had to be drawn to their plane shape, which, later, were worked to achieve the desired shape. The following action was to drill the holes, in the flat pieces, belonging to the inner and outer flame tube, the combustion chamber. The drills were made using a vertical drilling machine.

"Flat washers" will be fixed, later on, to the respective components, specifically, the nozzle guide vane system, the end-rear of the combustion chamber, and the casing. The next step was to mold the flat pieces of the combustion chamber, nozzle guide vane system, and casing to the required diameter. Coming to the end of the molding of the piece, the "flat washers" were welded to obtain the tubes and flat rings. The last component, the shaft, with the help of a two-dimensional sketch design, was manufactured with a lathe machine.

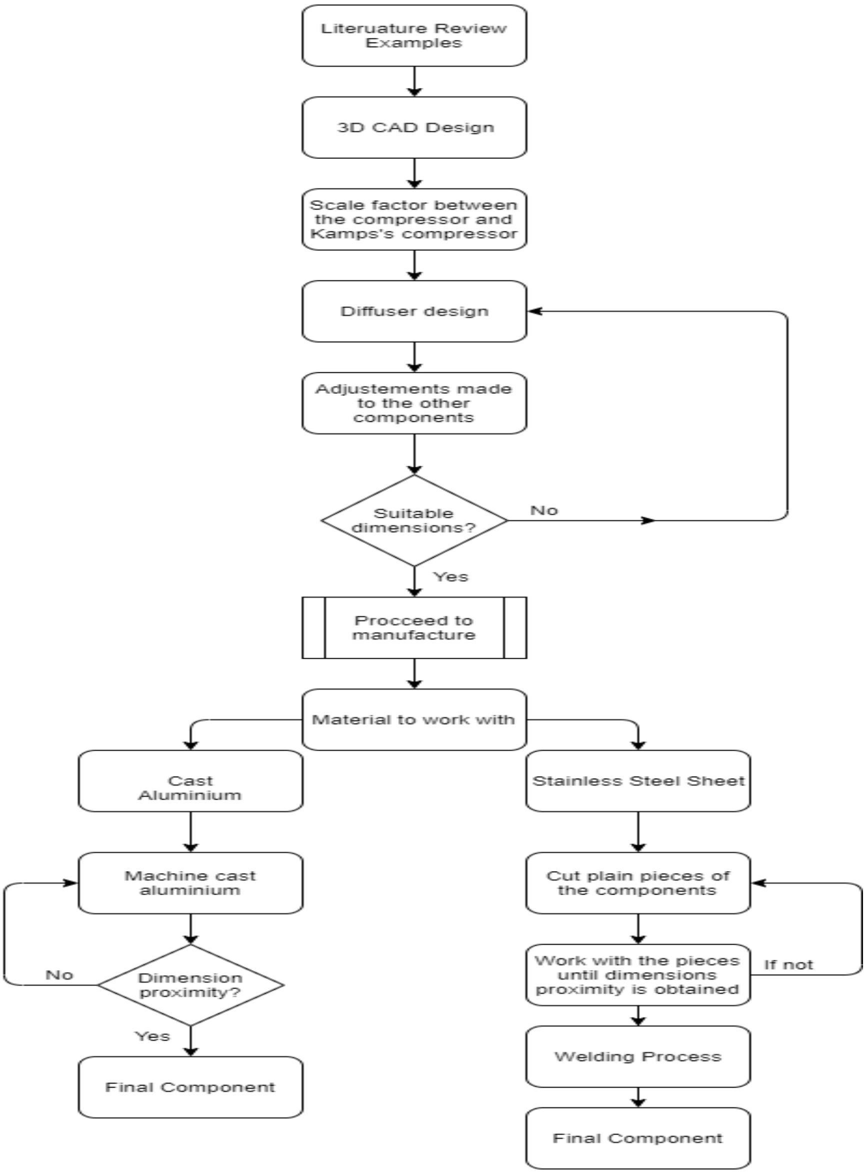

Figure 8: Diffuser design procedure

III. GAS TURBINES HISTORICAL REVIEW

The first concept came up at the times of Roman Egypt, created by Hero, or Hero of Alexandria. The aeolipile, the name of Hero's invention, is a radial steam turbine, that combines two nozzles, at opposite sides, where vapor water leaves due to the steam formed by boiling the water inside a sphere, causing the center of the sphere to spin, generating torque. An example of the steam engine is shown in Figure 9.

Figure 9: Aeolipile

The physical principle reaction was put into practice in the thirteenth century by the Chinese people using fireworks. After three centuries, in 1687, Sir Isaac Newton made a crucial advance in formulating the three laws of motion. These laws allowed us to take, within time, important steps towards the gas turbines. The first one was taken in 1791, by John Barber, an Englishman, who was granted a patent for the gas turbine thermodynamic cycle, known as the Brayton cycle, the same cycle of the actual gas turbines. Utilizing this cycle, Hans Holzwarth developed the electrical ignition of the mixture, in the combustion chamber, with controlled valves in 1908.

In 1913, an engine using the jet propulsion system was patented by René Lorin. The first sub-sonic ramjet, although, it was not possible to concretize the project due to the quality. material at that time. The materials could not resist the heat, as well as, the evolution of the jet propulsion system was on its first days, rebounding to the aircraft's efficiencies.

Jet propulsion engines were achieved in 1930 when Sir Frank Whittle patented the design of a centrifugal gas turbine for jet propulsion. Later on, in 1937, he made the first static test of the jet engine history. Despite Whittle made the first static test, it was Hans Joachin Pabst von Ohain, working for Heinkel aircraft company, who created a turbojet engine run by gaseous hydrogen, similar to Whittle's design, that was used as the propulsion engine for the aircraft He-178, realizing the first turbojet flight worldwide, in 1939. Three years later, Frank Whittle's engine was used for the first time as the propulsor of an aircraft.

The first axial-flow turbojet flight was in Germany, in the same year as Whittle's engine flight occurred. The axial turbojet, Jumo 004A, was the propulsion system of the aircraft Me-262. The leader of this project, chosen by Junkers company, was Anselm Franz. Despite Frank Whittle's engine not being built so quickly, he founded the basis of the modern gas turbine. The jet propulsion system was and still is, studied extensively to search for improvements, with a future successful application in this engine type. Only years after, the turbojet engine was applied to an aircraft, the idea of reproducing the same engine on a small scale started to appear. The miniature-turbojet history is difficult to date, however, it is assumed that it was started by Kurt Schreckling, a German technician and amateur astronomer.

Kurt was the first to replicate a turbojet on a small scale, opening doors for small or miniature-model jet engines. Gas Turbine Engines for Model Aircraft, the book from his authorship, explains how he built the engine, the FD 3/64, which created a starting point for miniature turbojets in the future. This enabled others to improve Kurt's turbojet, as well as, develop new small-scale gas turbines based on his engine, such as the KJ66. geologic time scale, which had taken almost 2 hundred years to evolve, might be numerically quantified. No longer did it have simply extraordinary positional importance, it now had absolute temporal importance as well.

IV. APPLICATIONS

Jet engines are used to propel commercial airliners and military aircraft. The simplest version of an aircraft jet engine is a turbojet. Turbojets were used on the first jet-powered aircraft, the German Messerschmidt Me 262 used in World War II.

Turbojets tend to be inefficient except at high speeds, so modern aircraft use turbofans instead. Since the basic operation of a turbojet is simpler, we will begin our discussion of jet engines with turbojets.

The main components of a turbojet are shown in the animation below. In a turbojet engine, energy is added to the air by the compressor and burners. The compressor increases the pressure of the air analogous to the way squid pressurize water with their powerful muscles before ejecting it from their funnel to create a jet. The burners increase the temperature of the air. The result is high-temperature, high-pressure air that contains a lot of thermal energy. Some of this energy is extracted by the turbine to run the compressor. The rest is converted to kinetic energy as it is accelerated by the nozzle to a high velocity to generate thrust. Use the arrows in the interactive animation below to step through descriptions of the different components and obtain more detailed information about their operation.

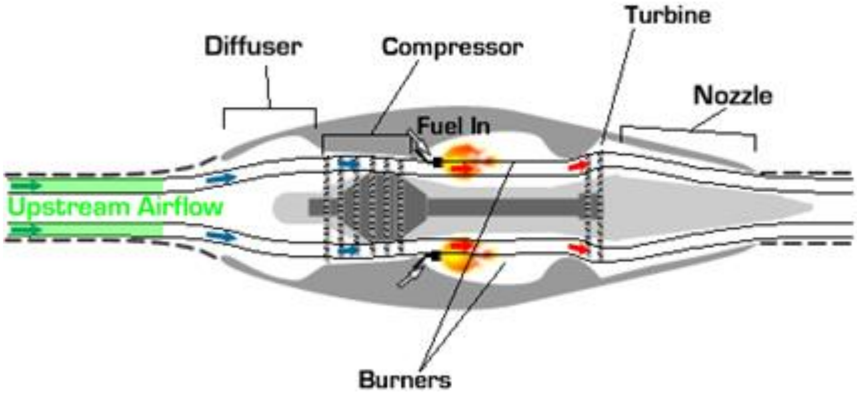

Figure 10:

The application of turbojet engines spans across various industries, with some of the key applications being:

1. **Aerospace**: Turbojet engines are extensively used in commercial and military aircraft for propulsion. They provide the thrust needed for takeoff, cruising, and landing. These engines power a wide range of aircraft, from small business jets to large passenger airliners and military fighter jets.
2. **Unmanned Aerial Vehicles (UAVs):** Turbojet engines are increasingly being integrated into UAVs for surveillance, reconnaissance, and other military and civilian applications. Their compact size and high thrust-to-weight ratio make them suitable for powering small and medium-sized drones.
3. **Missiles:** Turbojet engines are used in missile propulsion systems, providing high-speed thrust for guided missiles. They offer quick acceleration and high maneuverability, making them ideal for both air-to-air and surface-to-air missiles.
4. **Experimental and Research Aircraft:** Turbojet engines are utilized in experimental and research aircraft for testing new technologies, conducting aerodynamic studies, and exploring the outer limits of flight performance. These engines help push the boundaries of aviation and contribute to the development of advanced aerospace systems.
5. **Power Generation:** In certain niche applications, turbojet engines are used for power generation, particularly in remote locations where traditional power sources may be unavailable or impractical. These engines can drive generators to produce electricity for various purposes, such as powering equipment or providing emergency backup power.

Overall, turbojet engines play a crucial role in aviation, defense, and other industries where high-performance propulsion systems are required. Their versatility and efficiency make them indispensable for a wide range of applications, from powering commercial aircraft to driving cutting-edge aerospace technologies.

V. TYPES OF GAS TURBINES

Gas turbine history records show us the enormous and fast development of this engine. It is a product of a mixture of various areas like thermodynamics, mechanics, aerodynamics, and other areas, which are still being studied to the fullest extent for improvements. Only after understanding these fields, that the utility of a gas turbine be thought, of and, then, designed, depending on whether it is used for, a space mission, aviation transport, or air combat situations. Teams of scientists, engineers, and technicians created gas turbines with different ways of converting and supplying power, according to their purposes, such as jet propulsion engines: rocket, athodyd, also known as a ramjet, the pulse jet, and the turbo-jet, or, propeller jet engines: turboprop engine, turbofan, and turboshaft The ramjet, figure 11, is formed by a divergent inlet and a convergent or convergent-divergent exhaust. This engine requires forward motion to produce thrust. With no rotating parts, the air is forced to the divergent duct, followed by the combustion with fuel, where the gases will accelerate through the exhaust section to the atmosphere

Another jet propulsion engine relative, the pulse jet, figure 12, uses a similar duct to the ram-jet but is more robust because of the higher pressures involved. The air goes through open valves at the inlet and passes to the combustion chamber, where the combustion of fuel is realized, causing the gas to expand, thus, increasing the pressure. As a consequence of the rise, the valves close and the gas is ejected through the rear. Its high fuel consumption and unequal performance compared to the actual gas turbine make this engine inadequate for use in aircraft.

The rocket engine, figure 13, is distinguished from the other engines by not utilizing the oxygen from atmospheric air for the combustion but, instead, using a specific fuel, decomposed chemically with oxygen.

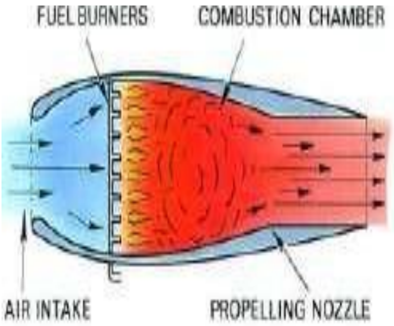

Figure 11: Ramjet

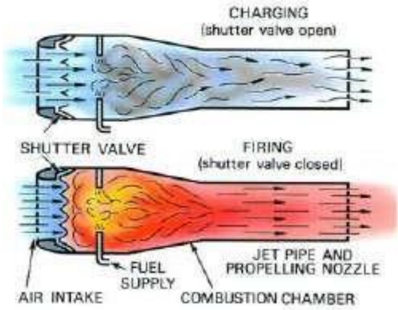

Figure 12: Pulsejet

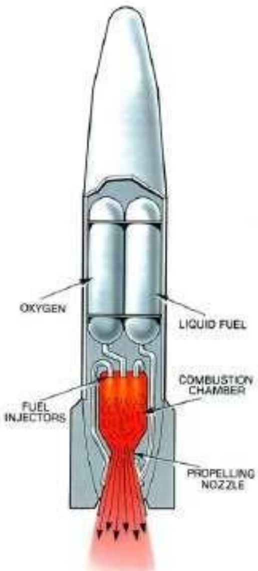

Figure 13: Rocket Engine

The turbojet, shown in Figure 14, is the junction of a compressor, combustion chamber, and turbine, called the gas generator, with an inlet and exhaust nozzle. The added exhaust nozzle will convert most of the energy of the airflow into velocity.

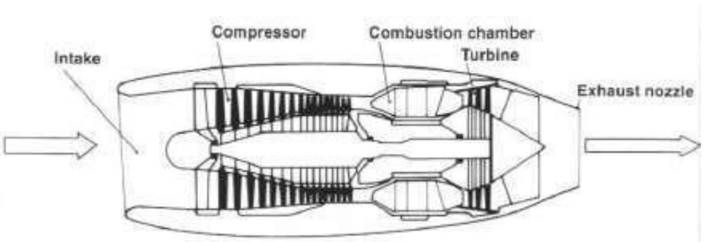

Figure 14: Turbojet

With the propeller/turbine combination comes the ducted fan, prop fans, and bypass engines. In the turboprop engine, shown in Figure 15, the two turbines' functionalities are to sustain the compressor work demand and make the propeller run. In a similar engine, the turboshaft, shown in Figure 16, the turbine drives the 10 compressor and the second turbine will drive the shaft, which in turn, is connected to a transmission system that rotates the helicopter blades

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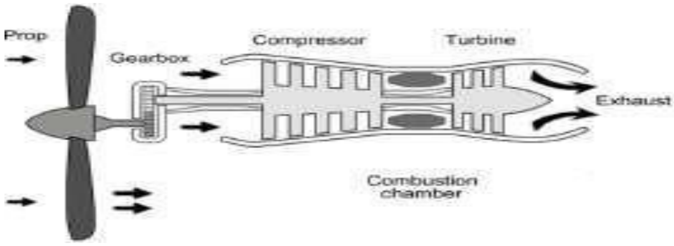

Figure 15: Turboprop Eller

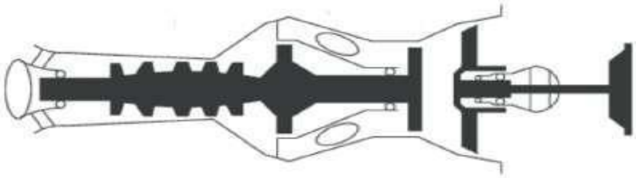

Figure 16: Turboshaft

The turbofan, illustrated in Figure 17, also has two turbines, in which, one, absorbs the energy from the hot airflow and, the other, utilizes the excess shaft work to drive a low-pressure compressor, a fan. It has a lower propulsive efficiency in comparison to the turboprop when they are being operated at the same cruise speed and lower velocities. Nevertheless, at higher velocities, the turbofan has the advantage. Engines like the turbofan started to be and still are, widely used due to high propulsive efficiency values when compared to a turbojet. These values are explained due to the bypassed airflow.

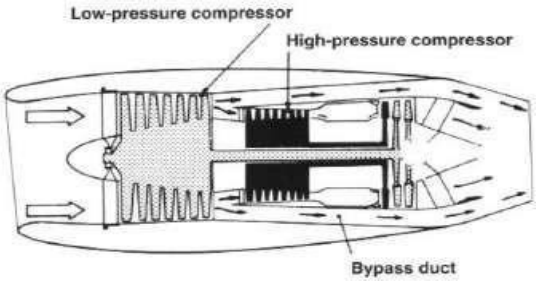

Figure 17: Turbofan

Bypassed airflow engines are distinguished into two types, low bypass-ratio and high-bypass ratio, in which bypass-ratio stands for the amount of air being bypassed about the air going through the engine's core. The engine is constituted with a high and low-pressure compressor and the matching turbines, that are driven by two coaxial shafts. The air is sucked by the low-pressure compressor, the fan, which will divide the air into two flows. Most of the air is ducted through the sides of the engine's core and a small part goes for combustion, being, then, the two airflows joined at the exhaust section.

This means a lesser fuel consumption than prior engines of similar thrust without this technology, allowing the engine to perform efficiently at high-altitude flights. The dominant use of this technology, in particular, high-bypass ratio engines, in the propulsion systems of civil aviation and long-range military missions are justified for the low fuel consumption, considered the most important performance parameterṅṅ. An example of a high-bypassed engine is demonstrated in Figure 18.

The turbojet is a simpler turbofan, which means, it does not have a bypassed airflow. Resulting in lower efficiency, although, it compensates with speed. These engines can reach supersonic speeds being one of the reasons for their usage in military aircraft.

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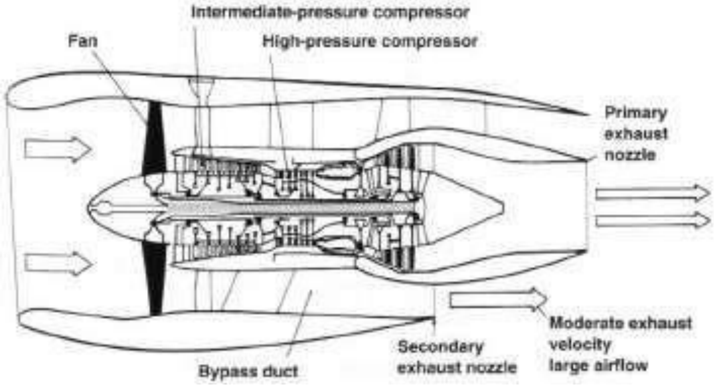

Figure 18: High-Bypassed Engine, Rolls Royce RB.211

VI. WORKING CYCLE

The working cycle subchapter aims to explain the functioning of an engine with a jet propulsive system, describing its thermodynamic cycle along with properties related to the latter. The working cycle starts from the intake of air into the compressor, whose job is to increase the pressure via mechanical shaft power. The pressure increase has a diminishable effect on the volume of the airflow, subsequently, raising the temperature of the air. The pressurized air is discharged to the combustion chamber, where fuel is added and burnt, raising the temperature to extremely high values. While the gas is burned, the volume, as the temperature, increases due to the open structure of the combustion chamber, maintaining the pressure constant. The combustion process raises the energy state of the molecules to high levels, enabling the necessary amount of energy to be effectively explored by the turbine. As an effect of the work extracted from the gas, the turbine starts to rotate, converting the gas energy surplus to mechanical power by generating motion. This spinning motion will force the compressor wheel to rotate due to the work provided by the turbine, which is transferred by the rotation of the shaft to the compressor, on the other end of the spool. At this stage, the gas variables, pressure, and temperature decrease, whereas, the volume increases. Finally, the gas flow reaches the final stage, at the exhaust nozzle, where the gas is ejected to the ambient at high velocities, producing thrust.

There are three main conditions in the engine cycle to retain:

In the compression, there is an increase in pressure with a consequent decrease in volume and temperature rise.

In the combustion, an increase in temperature occurs, while the pressure remains constant and the volume increases.

In the expansion, the volume rises along with a decrease in pressure and temperature.

The working cycle of a gas turbine is, generally, compared to the working cycle of a four-stroke piston engine taking into account the four similar stages of each engine. Both engines initiate their cycle by the induction phase, followed by compression, combustion, and expansion. Nevertheless, all the stages of the piston engine are performed inside a cylinder, while in a jet engine, each component is assigned the corresponding function, resulting in a continuous action, instead of intermittent. Moreover, the combustion in a jet engine occurs at constant pressure, as opposed to the reciprocating engine, where the combustion process takes place in a closed space. Therefore, the jet engine is capable of operating large masses of air with lightweight components. At the final stage, the exhaust phase, the gases, expanded by the turbine, leave the nozzle, generating a propulsive force essential to this engine. In contrast, the exhaust gases of the piston engine do not have the same significant effects. Considering the differences stated, the gas turbine engine removes three idle strokes, consequently, more fuel can be burnt in a shorter period. Since the turbo-jet engine is a heat engine, with more fuel burnt, the higher the temperature of the combustion chamber is, hence, a substantial expansion of the gases occurs. Furthermore, a greater amount of power is produced for a given size. For a piston engine to generate the same amount of power, it would have to be extremely large, and heavy and the manufacture would be a serious challenge.

As the gas is discharged from the nozzle, it will be, progressively, dispersed to the ambient conditions, reverting to its original state. The gas throwback to its original condition implies that the state variables also revert to their original conditions, termed a reversible process. A process to be considered reversible has to combine internal and external reversibility. Suppose the gas states could be restored in a reverse sequence, while a system is submitted to a process in which the pressure and temperature gradients are minor. In that case, the process is defined as internally reversible. Meanwhile, for a process to be considered externally reversible, the atmospheric changes that go along with the process can be reversed in sequence. However, the reversible process is impossible to achieve due to the irreversible factors, for example, temperature, pressure, and velocity gradients triggered by heat transfer, friction, chemical reaction, and work applied to the system. Despite the irreversibility of the real processes, the reversible process is standardized to estimate the success of real processes taking into account the losses, as well as, to enable the thermodynamic relations to be derived to estimate reality.

THERMODYNAMICS CYCLE

It is further presented notions to be acknowledged, to understand the conditions and properties behind the ideal thermodynamic cycle that comprehends all the gas turbines, in particular, the turbojet engine.

- Steady-flow process

The gas turbines are built, generally, for continuous operation, in which there is an approximation of the conditions they operate on. Assuming it performs under the same conditions as time passes, the process is termed a steady-flow process.

It means the fluid properties remain the same throughout the whole process. Flowing in a control volume, the fluid properties can alter from different fixed points but stay the same, from the start to the end. As a result, the mass, m, volume, V, and total energy rate or total power, E, are constant throughout this process.

The conservation of mass principle is applied, stating, that considering a control volume, the total rate of mass entering equalizes the total rate of mass leaving it. Since there is no increase or reduction of mass, the mass flow rate, $\dot{m}$, is equal from the beginning to the end of the process. It is expressed in the form of,

Considering it for a uniform single stream, denoting the inlet and exit states, 1 and 2, respectively, the mass balance becomes,

$$\dot{m}1 = \dot{m}2 \longrightarrow \rho 1V1A1 = \rho 2V2A2 \quad (2)$$

P, V, and A represent density, flow velocity, and cross-sectional area.

In the context of the total energy rate, the energy remains the same within a control volume, indicating no changes in the total power. This simplifies the energy balance to,

$$\dot{E}in = \dot{E}out \quad (3)$$

Remembering that the energy transfers occur in the form of mass, $\dot{m}$, work, W, and heat,

Q, the energy balance is represented as,

$$Qin + Win + \Sigma \dot{m} \theta = Qout + Wout + \Sigma \dot{m} \theta \quad (4)$$

Inout

Where the energy of a flowing fluid, θ, is described as,

$$\theta = h + ke + pe \quad (5)$$

Where h, ke, and pe are defined as enthalpy or internal energy, kinetic energy, and potential energy.

Heat and work interaction is defined by, a heat transfer into the system, heat input, and the work produced by the system, work output. Considering there are no changes in kinetic and potential energy, the energy balance is expressed in the way.

$$Q - W = h2 - h1 \quad (6)$$

- Stagnation Properties

In control volumes analysis, it is usual to put together the internal energy and the fluid energy to form one variable already referred to, specific enthalpy, h. For most of the cases, the kinetic and potential energy are disregarded, defining the enthalpy as the total energy of the fluid.

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However, when the kinetic energy is not neglected, generally, it is appropriate to convert the kinetic energy into the enthalpy of the fluid, combining them into one term defined as stagnation or total specific enthalpy, shown in equation 7.

$$ho = h + V\,2/\,2 \quad (7)$$

In equation 7, the enthalpy is distinguished by two types, the static and stagnation-enthalpy, h and h0, respectively.

As a result of the kinetic energy conversion to enthalpy, the temperature and pressure increase. These fluid properties are recognized as stagnation properties or isentropic stagnation properties. Enthalpy and the stagnation temperature of an isentropic stagnation state, and actual, are the same, given the fluid is an ideal gas.

The actual stagnation pressure differs from the isentropic stagnation pressure because the entropy rises due to fluid friction [14]. Assuming the fluid as an ideal gas, the enthalpy can be substituted by the constant specific heat times the temperature, shown in equation 9.

$$cp = cpT + V\,2/2 \quad (8)$$

Becoming,

$$To = T + V\,2/\,2cp \quad (9)$$

Where T0 indicates the stagnation or total temperature, in other words, the temperature that the ideal gas reaches when it is brought to rest in an adiabatic process, and, the term V 2, represents the temperature increase throughout the process named dynamic temperature.

The relation between the temperature and pressure is demonstrated in Equation 10.

$$P0\,/\,P = T0\,\gamma{-}1/\,T \quad (10)$$

Where, P0 and γ, are termed as stagnation pressure and specific heat ratio.

BRAYTON CYCLE

It is a thermodynamic cycle, idealized, present in all gas turbines equipped with fundamental components, such as the compressor, combustion chamber, and turbine. The cycle is divided into two types: open and closed cycle. The former cycle, consists of air, at atmospheric conditions, pulled to the compressor that raises the temperature and pressure of the air.

The pressurized air will follow to the combustion chamber, where it is mixed with fuel, succeeded by combustion, at constant pressure. When the combustion process has been finalized, the gas exits to the turbine, at extreme temperatures, where the expansion of the gas occurs. At this phase, the interaction of the gas with the turbine is used to drive the compressor. The remaining work of the gas is taken to accelerate the fluid ducted by the exhaust nozzle to the exterior. The reason for the gas being expanded to the exterior, the cycle is classified as an open cycle. On the contrary, if the gas had been recirculated, the cycle would be considered to be closed. Figures 19 and 20, describe an open and closed cycle.

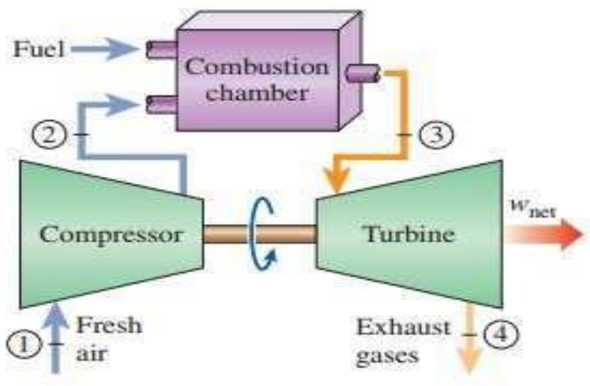

Figure 19: Open cycle

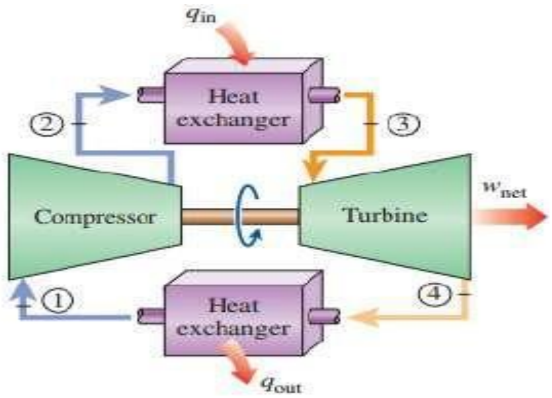

Figure 20: Closed cycle

Noticing in the closed cycle, the combustion process was substituted by a constant pressure additional heat, accompanied by the replacement of the exhaust process for a heat rejection process, at constant pressure, to the exterior.

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The turbojet engine working cycle corresponds to an open Brayton cycle, which is the usual type of cycle for gas turbines. Figure 21 illustrates the components of a jet propulsion device with the corresponding Brayton cycle.

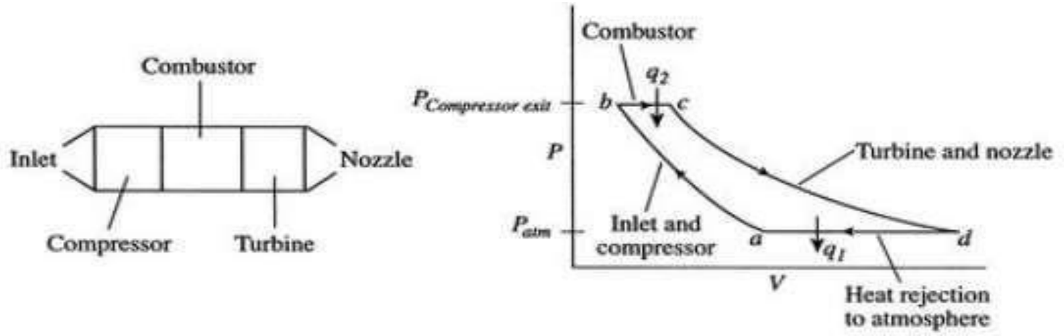

Figure 21: Jet Engine Components and analogous thermodynamic states

The thermodynamic states observed in Figure 12, are distinguished in four processes. The legend of this cycle is formulated in the following manner:

a-b: Compression at the inlet and compressor, in an isentropic process.

b-c: Combustion of fuel at constant pressure.

c-d: In the expansion, the volume rises along with a decrease in pressure and temperature.

CYCLE BEHAVIOUR ANALYSIS

Cycle analysis is a process to obtain estimates for performance parameters such as thrust or specific fuel consumption, calculated after assuming some conditions and design specifications, presented below.

Conditions

- The working fluid is considered an ideal gas with constant heat capacity and specific heat ratio.
- Isentropic Compression/ Expansion .
- The external source of heat for combustion and fuel mass is disregarded.
- Design Atmospheric pressure and temperature values.
- Compression ratio.
- Inlet Mach number.

In this subsection, the ideal and actual behavior of the components are presented, indicating the temperature and pressure for each station. The stations will be distinguished by a number for easier referencing, as demonstrated in Figure 22. The actual turbojet cycle analysis is presented in Appendix D.

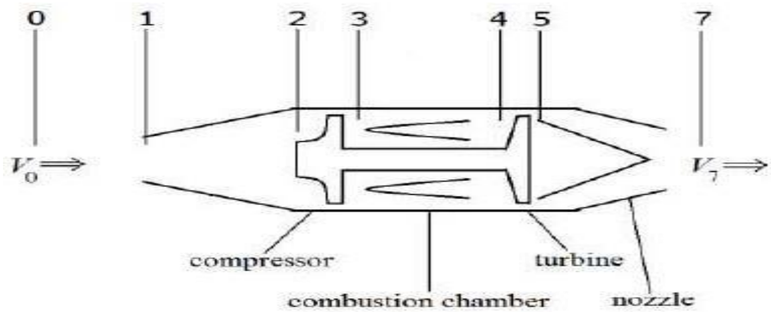

Figure 22: Turbojet station numbering

- Stations descriptions

0. Free Stream
1. Inlet Entry
2. Compressor Entry
3. Compressor Exit
4. Turbine Entry

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5. Turbine Exit
6. Nozzle Entry
7. Nozzle Exit

VII. CONCLUSION

In conclusion, this dissertation outlines the development of a small-scale turbojet based on the model turbo IHI RHB31 VZ21. Despite successful design and manufacturing of various components, challenges arose in producing extremely small parts, such as the diffuser and compressor shroud, leading to the inability to achieve the primary objective.

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