DESIGN AND DEVELOPMENT OF TURBO JET ENGINE AND PROPULSION

Abstract

The design and production of a compact gas turbine engine was the main objective of this important qualifying project. The parts that were made were the axial turbine, stator, diffuser, compressor intake, shaft, outer casing, combustion chamber, fuel distributer, exhaust nozzle, and inlet flange. We looked at the available literature on gas turbine engine parts, then designed and produced each part as a result. We then put our engine together and made testing preparations.

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INTRODUCTION

The gas turbine engine is a machine that, according to the thermodynamic Brayton Cycle, does work by harnessing energy from a working fluid and converting the energy into a useable form. Various types of gas turbines are designed to perform a range of tasks but all operate on similar principles. Air enters the engine, is compressed, mixed with fuel, combusted, and then expanded through a rotating turbine. Common applications of modern gas turbines include: producing auxiliary power for ground or aircraft systems, propelling military aircraft at supersonic speeds, and driving the rotor system of helicopters. Due to the extreme temperatures and high rotational speeds experienced by engine components, design and construction of a gas turbine demands accuracy, informed material selection, knowledge of thermodynamics, and the ability to model and machine metal components. As material processing techniques advanced, it became possible to manufacture gas turbine engines small enough to power radio controlled (RC) airplanes. Modern gas turbines for full size aircraft generally utilize axial compressors and turbines with multiple stages of blades. These multi-stage components increase efficiency, pressure ratios, and performance characteristics However, RC jet modelers found that small engines can be reasonably efficient and powerful with single stage compressor and turbine stages. A centrifugal compressor matched to an axial turbine has become a common design among RC jet enthusiasts. With this simplification, along with advancements in CNC machining and 3D 3odelled3, it is possible to manufacture a complete miniature gas turbine with a relatively small investment Although miniature gas turbines are now available for sale from a number of manufacturers, the secrets of design and construction are still somewhat hidden from the end customer. Accurate analysis of performance is elusive even with the utilization of modern software, and an iterative design process offers the soundest path toward new engine development. However, a number of publications are available that instruct the ambitious RC jet enthusiast on how to manufacture an engine with amateur means. The goal of this project is to call on the literature available regarding small gas turbines in order to design and manufacture an engine that is self-sustaining. In order to expedite the design process, efficiency and thrust production are not prioritized. Due to budget and time restrictions we are unable to complete multiple iterations of a new engine. Therefore, we rely on engine designs currently developed to aid in the design of our major components. Subjects such as new aerfoil design for turbine blades, nozzle efficiency, and combustor efficiency can be the subject of years of research and investment. For this reason, we drew on industry standards and recommendations of modelers to design some of our components. We realized early that two crucial components, the centrifugal compressor and ball bearings, would be impossible to design and manufacture given the time frame. We made the decision to purchase these components in order to make our project more feasible given the restrictions. This project culminated in the manufacture of twelve major components.

- Compressor inlet shroud
- Diffuser
- Power transmitting shaft

- Annular combustion chamber
- Fuel distributer
- Stator
- Stator/turbine housing
- Axial turbine
- Exhaust nozzle
- Outer casing
- Inlet flange

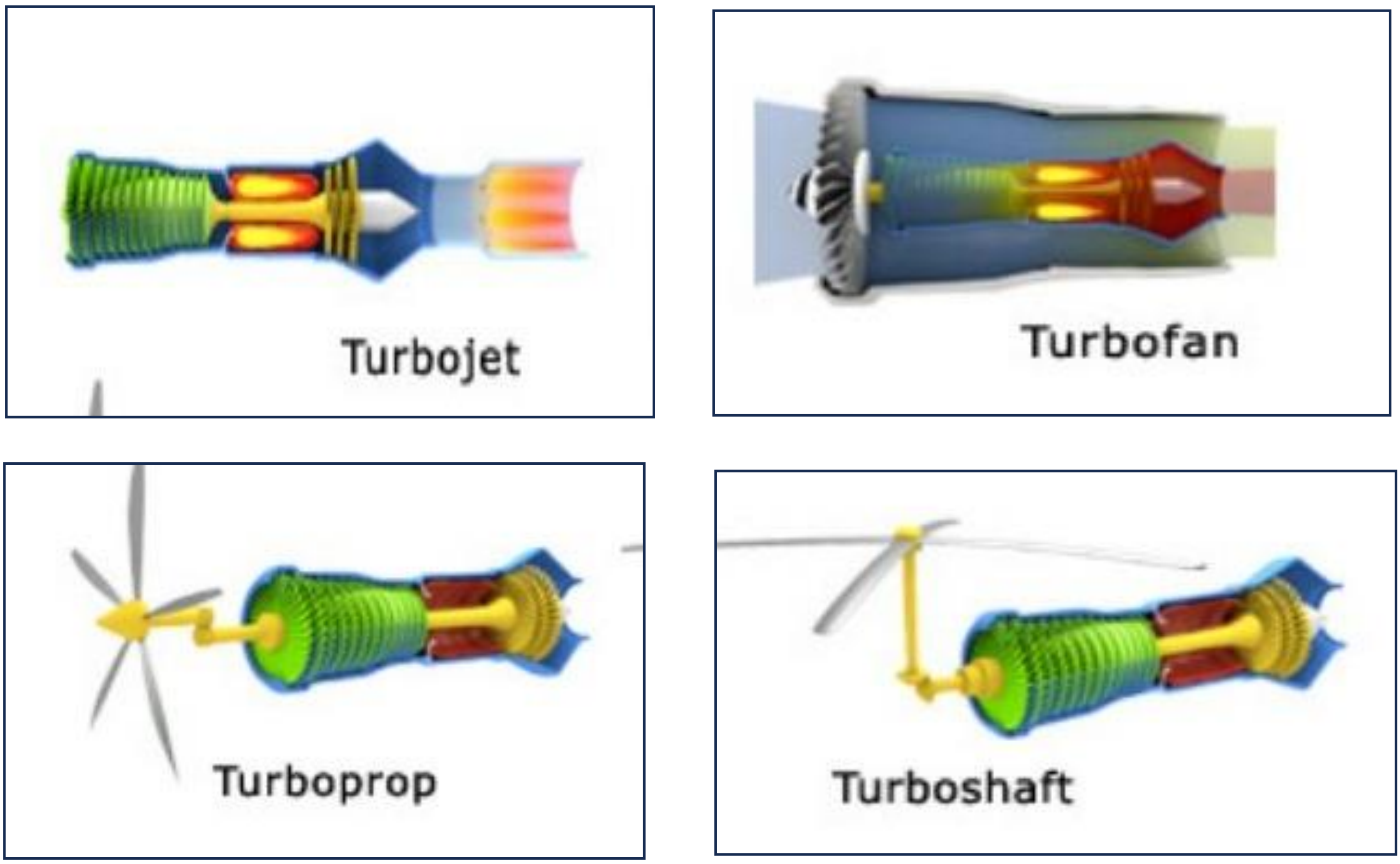
Additionally, we assembled our components and added a fuel injection system and bearing lubrication system. Due to time constraint, we were unable to implement a throttle mechanism or construct a simple and safe engine stand and were not able to test the engine. Each component listed above was first 4odelled with Catia v5 Software and then manufactured with the material processing capabilities available in Worcester Polytechnic Institute's Washburn and Higgins Labs. Throughout the experience, our team furthered our design and manufacturing skills through manual and CNC milling and turning, TIG welding, sheet metal forming, and regular engineering troubleshooting.

2.0 BACKGROUND

This chapter reviews previous research on gas turbines with an emphasis on small/miniature sized turbojets. We provide an introduction to gas turbines and their use as well as methods for conducting theoretical cycle analysis. Additionally, we introduce the components that constitute a modern small gas turbine.

4.0 GAS TUBINES

A gas turbine is a type of continuous, internal combustion engine that contains three major components: a compressor, a combustor, and a turbine. A basic configuration, referred to as the turbojet, consists of an inlet nozzle where air at free stream velocity is directed into a compressor. The air is accelerated and compressed across the compressor stage and then redirected into the combustion chamber. Fuel is injected into the chamber, combined with the high-pressure air, and ignited to create combustion. The hot gas, which has expanded in the combustion chamber, is forced through the turbine blades resulting in rotation of the shaft which ties the turbine to compressor. From here the exhaust gas is accelerated through an outlet nozzle. The high velocity exhaust is at a speed much greater than the free stream velocity and therefore produces thrust The basis for the creation of thrust is Isaac Newton's second law of motion, force is equivalent to mass times acceleration. According to the principles of conservation of momentum, the thrust force created by the turbojet is equal to the mass flow rate of the exhaust gas multiplied by the velocity relative to the free stream velocity of air entering the compressor. The more fuel that is consumed by the engine, the more thrust is created, assuming constant efficiency. One method for increasing the amount of thrust is by afterburning, also known as thrust augmentation. This design incorporates a separate burner that combusts extra fuel and releases hot exhaust gases downstream from the turbine Afterburners can substantially increase thrust at the expense of rapid fuel consumption. However, afterburners are primarily used in military aircraft to achieve supersonic flight. Some gas turbines do not generate thrust and instead have become a popular method for power generation due to increases in efficiencies Although these industrial applications for gas turbines exist, this paper focuses on aircraft propulsion applications. Four main types of turbines utilized in the aerospace industry are the turbojet, turbofan, turboprop and turboshaft. Turbojet and turbofan engines provide thrust generated from reaction forces created by high velocity exhaust gas leaving the outlet nozzle. The turbofan is the most common type of engine used in the aerospace industry It utilizes a fan that is upstream the compressor, which is also driven by the turbine. Air bypasses the compressor and rejoins the flow downstream of the turbine adding “cold thrust.” This design achieves better fuel efficiency than turbojet engines while operating at cruising speeds common to civil airline travel. The turbojet engine, unlike the turbofan, does not allow air to bypass the compressor, it is simple by design and the earliest type of turbine propulsion engine. Turboprop and turboshaft engines use exhaust gases to drive a separate turbine that drives a propeller. The difference between the two is that the turboshaft utilizes all exhaust gas to drive the propeller, whereas the turboprop also uses some of this exhaust gas to produce thrust. Turboshaft engines are commonly used in helicopters, such as the Figure below gives a visual representation of these four engines.



2.2 components

2.2.A. compressor

As we now know, the compressor is the stage of the engine which creates high enough pressure to achieve combustion. The two types of compressors commonly used in turbojet engines are axial and centrifugal The axial compressor directs the air flow parallel to the rotational axis whereas the centrifugal design directs the flow radially outward, perpendicular to the rotational axis. Small gas turbines, that produce less than 5 MW, are often designed around centrifugal compressors. Although these are less efficient than multi-stage axial compressors, centrifugal compressors are reliable and able to produce pressure ratios in excess of 8:1 with a single stage. The pressure ratio is equal to the total pressure downstream the compressor divided by the pressure at the compressor entry.

2.2.B. diffuser

The purpose of a diffuser is to decelerate the speed of the incoming compressed fluid, converting the speed of the gas into pressure. Essentially, the diffuser converts high speed air in the form of kinetic energy into potential energy in the form of high pressure. There are a variety of acceptable diffuser designs for small gas turbines. One design, the radial wedged diffuser, has become popular among manufacturers of small gas turbines for model aircraft The blade configuration of these diffusers can vary greatly and still perform adequately, some are curved in the direction of rotation of the impeller while others curve in the opposite direction. However, perhaps the most desirable blade design characteristic for small gas turbines is that the blade widens to provide sufficient surface area for bolt holes These bolt holes provide a convenient location that allows the manufacturer to bolt the diffuser, compressor and inlet shroud into a ridged body.

2.2.C. Turbine and stator

Turbines, like compressors, are designed as either axial or radial. Axial-flow turbines are the most widely used because they offer the possibility for higher mass flow rates than that of radial turbines. Typically, axial-flow turbines consist of multiple stages in order to increase efficiency and thrust production. However, when designing small gas

turbines single stage axial turbines are often used. The turbine stage usually consists of nozzle stationary guide vanes, also known as a stator. Stator blades are aerofoils with their leading edges facing the combustion chamber Their purpose is to reduce the phenomena known as swirl and allow air to accelerate into the turbine blades. The stator directs exhaust gases in the axial direction towards the turbine blades while

increasing the absolute velocity and kinetic energy of the exhaust gases. The stator has a similar yet opposite role to that of the diffuser in the compressor stage. In the diffuser, the area between the adjacent blades increase in the downstream direction whereas in the stator this area increases. The stator and turbine must contend with extremely high thermal loads. By raising the turbine inlet temperature, more thrust per unit mass flow rate is generated The turbine also operates at extremely high angular velocities. These criteria have driven the development of new materials and cooling techniques used in this stage of the engine. Even small turbine blades can encounter exhaust gases with temperatures in excess of 1000 degrees centigrade while rotating upwards of 100,000 RPM. Due to high pressures, temperatures, and peripheral blade speeds nickel-based super alloys are often used

These materials must also have high resistance of creep due to their continuous use under these conditions. Various companies have developed Nickel-Chromium super alloys for use in turbine blades. Common trade names for these alloys include: Inconel 625, All temp 625, and Chronin 625.

2.2.D. combustion chamber

The purpose of the combustion chamber is to retrieve air from the compressor stage and deliver it at much greater temperatures to the turbine stage, this is where heat is added to the cycle by burning fuel. The diffuser section of the compressor stage decelerates the airflow in order to increase pressure before it reaches the combustion chamber. This high-pressure air stores potential (pressure) energy and will produce better combustion and cycle efficiency. Energy is further increased through combustion of injected fuel, usually kerosene, and the high-pressure air. Average air/fuel ratios range from around 45:1 to 130:1 for the entire combustion chamber however fuel will only burn efficiently around the stoichiometric air/fuel ratio, 15:1. As this project is concerned with combustion chamber design, it should be noted that many advancements in combustion chamber design have been founded upon empirical data and experimentation Therefore, design of combustion chambers relies heavily on the analysis of previous, similarly designed systems. Two common types of combustion chambers have been developed, the cylindrical, or can chamber, and the annular chamber. A single annular chamber can be employed quite effectively in a turbojet engine while being conducive to minimizing weight, cost, and complexity of design Our research focuses on small, annular combustion chambers that can be utilized in miniature turbojet engines.

2.2.E. Exhaust nozzle

The purpose of an exhaust nozzle is to create thrust by converting the potential energy incoming gas into kinetic energy. In the nozzle, the mass flow rate is constant. As velocity increases in the direction of flow, pressure decreases. Typically, length is not a crucial design consideration however, losses due to friction can be excessive if the nozzle is too long. In an ideal nozzle there are minimal kinetic energy losses due to this friction. Well-designed nozzles can commonly achieve efficiencies up to 90%. Common nozzle designs for aircraft includethe converging nozzle and theconverging-diverging nozzle. Converging nozzles are used for aircraft flying at subsonic speeds, speeds which are less than the speed of sound throughout the nozzle. Converging-diverging nozzles are used to achieve supersonic flows, which are typically used in military aircraft. Flow through convergent nozzles are subsonic when the pressure at the exit is equal to ambient pressure The exit area of a convergent nozzle is known as the throat. This project focuses on the use of a converging nozzle in order to reduce noise and avoid shockwaves

2.2.F. Fuel system lubrication and bearing

Gas turbines can utilize an assortment of liquid or gaseous fuels. Gaseous fuels do not require vaporization to achieve combustion. However, liquid fuels present a lower risk of gas escape and are therefore easier to handle and store. For this reason, liquid fuels arecommon in aircraft engines. The desirable characteristic when choosing a fuel source is a highspecific heat of combustion. Also known as the specific energy, this property is defined as the energy per unit mass of a fuel . High specific energy results in lower quantities of fuel needed to achieve high levels of energy production. Common turbine fuels include: diesel, kerosene, propane and butane, which all have specific energy values ranging from 40-50 MJ/kg. Table 1 shows some common specific energy values for different fuel sources.

Fuel	Specific energy (Mj/Kg)	Density (Kg/m^3)
Methane	55.6	423
Propane	50.3	585
Butane	49.5	601
Gasoline	47.3	716
Kerosene	46.2	830
Diesel	44.8	830

The stoichiometric air/fuel ratio of the mixture is essential to achieving combustion. This ratio defines the amount of air consumed by the engine compared to the amount of fuel consumed. For example, gasoline engines require an air/fuel ratio of 14.7:1, meaning for every 1 part of fuel, 14.7 parts of air are required to achieve combustion. The proper mixture of fuel and air is critical in achieving high engine durability and performance. Any excess fuel will not combust and form deposits on combustion chamber components such as injectors, vaporization tubes or even turbine blades (Flack, 2005). This can further lead to the development of hotspots and inefficient combustion. Another important consideration is determining the minimum required fuel consumption for the engine. By calculating the heat output and then using the specific density and energy of the fuel, the minimum fuel flow requirement can be determined.

$$Q=m°C\Delta T$$

3.0 Methodology

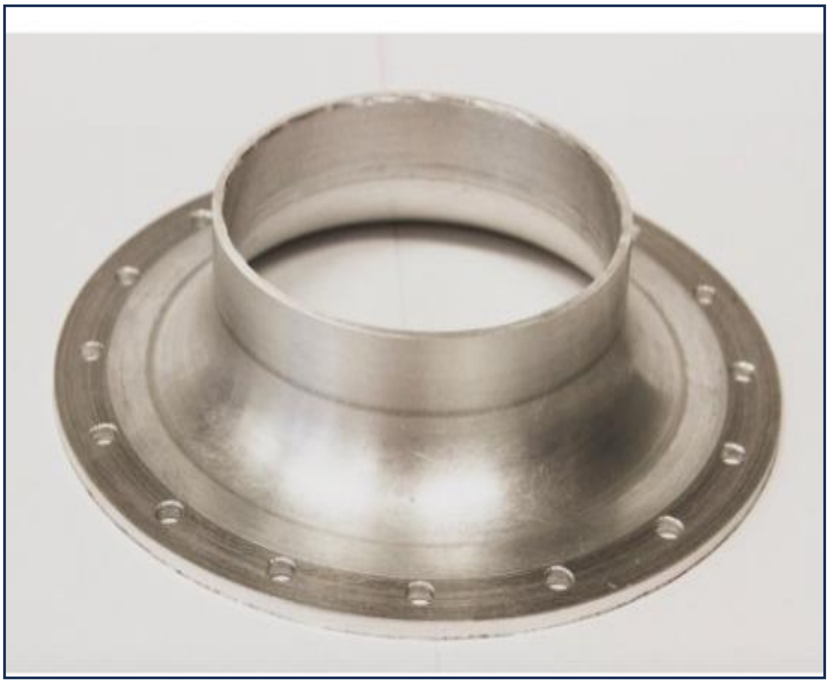
In this topic we will explain how we designed and manufactured each component of our engine. We present each component and outline the considerations and challenges encountered during the design process. Additionally, we discuss the materials and manufacturing methods used to produce each component

3.1 compressor

In order to simplify the design and manufacturing process and complete the project within the given time constraint, our team decided to purchase a compressor wheel. After examining the literature regarding compressor wheels used in small gas turbine engines, we concluded that a single stage axial compressor would not offer a high enough compression ratio or efficiency to be used in an engine of our size utilize a centrifugal compressor in order to achieve adequate compression ratios and efficiencies. For these reasons, we chose to investigate centrifugal compressor wheels used in automotive turbochargers. We found that the Garret GT4202 compressor wheel provided a mass flow rate and pressure ratio, at our desired RPM

3.2 Inlet shroud

The primary challenge we faced while integrating the GT4202 compressor into our engine design was obtaining the profile of the rotating compressor wheel. Computer Aided Design (CAD) models of the compressor are proprietary and unavailable to consumers. However, it was essential that we find these dimensions in order to design an inlet shroud. The space between the compressor blades and the inlet shroud cannot exceed 40/1000 of an inch and to achieve reasonable efficiencies, should be as small as possible The shroud was machined from a six-inch bar stock of 6061 t651 aluminium and was turned on a Computer Numerical Control (CNC) lathe in the Worcester Polytechnic Institute (WPI) Washburn Shops. A total of sixteen bolt holes were drilled around the perimeter of the shroud in order to facilitate assembly. The completed inlet shroud can be seen below in Figure



3.3 Diffuser

he first decision to be made when designing the diffuser stage was which diffuser style to choose: veined or channel. After reviewing the literature on small gas turbine engines and other similar designs, we chose the wedged channel diffuser design. This same style diffuser was used successfully in the KJ66 engine. Additionally, the wedges provide a convenient location to drill bolt holes in order to fasten the inlet shroud. Considering the diffuser does not experience extremely high temperatures, we decided to machine it from 6061 t651 Aluminium. Aluminium provided us with adequate strength for the components purpose, while enabling an easier machining process. We machined the part on a Haas VM-2 vertical milling machine. After the operation to machine the wedges was completed, we drilled the holes with a separate CNC program and hand tapped the holes. In order to machine the vanes on the side of the diffuser, we fixed the stock in an indexing head and moved the indexing head a determined angle evenly properly locate the fins. Finally, we implemented a program to machine the holes on certain fins. The completed diffuser can be seen in Figure

3.4 combustion chamber

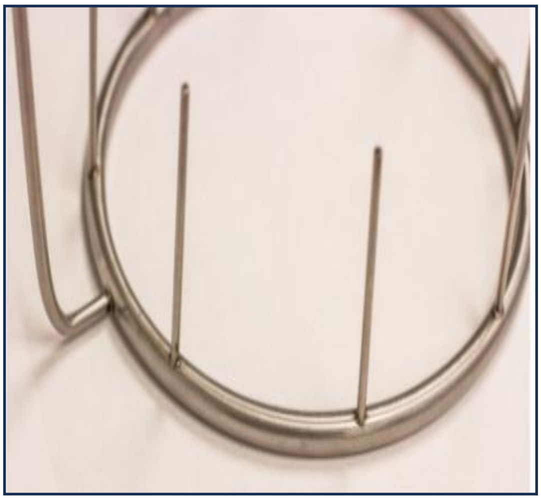
Based on the literature reviewed, our team decided to manufacture an annular combustion chamber. Annular combustion chambers allow the manufacturer to create an engine of smaller diameter, which we found to be desirable. Additionally, we determined utilizing another combustion chamber design, such as the can combustor, would have provided a more substantial manufacturing challenge. Because most combustor design is based off empirical data, and we were not focused on optimizing a design, we decided to model our combustor after successful combustion chambers that have been widely implemented on turbocharger based amateur gas turbine engines. Our combustion chamber design incorporates an outer line and inner flame tube. Both of which contain 3 separate zones of holes. Primary, secondary, and tertiary holes in the combustor that assist the mixing of air and fuel. Due to its ability with withstand extremely high temperatures, we chose to manufacture our combustion chamber out of Inconel 625. A local company donated a 0.02-inch-thick sheet of the material which we then cut into four pieces. We rolled two pieces into the inner flame tube and outer line while the remaining two pieces were cut into two annular end caps. We then welded eight vaporization tubes, about 5 inches long and ¼ inch diameter, to the turbine side endcap. Finally, the two caps were welded to the outer line and the compressor side cap was welded to the flame tube, completing the assembly. An image of the completed combustion chamber can be seen in Figure

3.5 Shaft housing

We designed the shaft housing to accommodate the shaft and bearing dimensions. There is substantial flexibility regarding the design of the housing outer profile, various models can be seen throughout the world of miniature gas turbines. We decided to go with a simple, straight profile that widens at one end to allow space for bolt holes to fix the housing to the diffuser. The inner tube incorporates two bearing seats. The bearing seat at the diffuser end, which can be seen in Figure 14, accommodates half of the bearing thickness. When bolted to the diffuser, the shaft housing sandwiches the bearing halfway between the diffuser and he housing. The turbine end bearing seat is designed to allow space for a spring and sleeve system which places ten pounds of preload on the bearing. The purpose of this system is to increase the longevity of the bearing when experiencing high rotational speeds and temperatures near the turbine. The shaft housing was manufactured from a three-inch diameter, 6061 t651 aluminium rod. We first drilled and then bored the inside diameter to accompany the shafts dimensions. We then drilled and bored the inner area on the turbine side to accommodate the sleeve spring system and turned down the outside. The component was then flipped, centered and then bored and turned again to achieve the features on the compressor side. Finally, eight holes were drilled on the base on the shaft housing in order to fixture it to the diffuser. The completed shaft housing can be seen in Figure

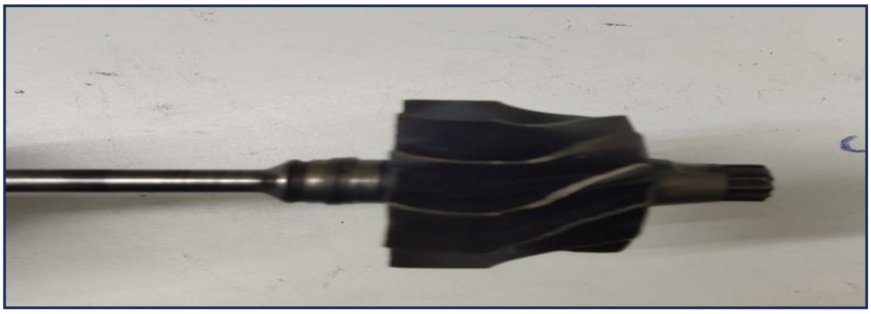
3.6 fuel distributer

The purpose of the fuel distributor is to transport fuel from an outside source into the vaporization tubes of the combustion chamber. We chose a simple distributor designed similar to those seen in many small gas turbines. The distributor consists of eight, 0.08-inch diameter fuel injectors mounted normal to our ¼ inch injector ring. Each injector is matched to a corresponding vaporization tube on the turbine side endcap of the combustion chamber. The injector ring sits on the outside of this endcap where it is held in place by the stator housing. Tubing connects to the ring which runs alongside the length of the combustion chamber and through the outer case of the engine. It is here where the distributor connects to an outside fuel source. The fuel distributor was manufactured entirely from 316 stainless steel tubing. We first cut and rolled the larger tubing to make the five-inch diameter injector ring. Next, we drilled eight 0.08-inch diameter holes in the injector ring to accommodate the fuel injectors. An additional hole was drilled perpendicular to these holes for the fuel supply line. We then cut eight, 0.08-inch diameter fuel injectors each 3 inches in length. We determined that conventional welding methods would not be feasible due to the small diameter and wall thickness of the tubing. Therefore, we decided to reach out to a local company with laser welding capabilities. They agreed to weld the assembly together and the resulting fuel distributor can be seen in Figure



3.7 Turbine

The turbine was initially designed to be machined from Inconel 718 four-inch bar stock due to the materials ability to maintain strength during high temperature rotation. In order to achieve the desired aerofoil geometry and a curved channel floor between fins, we attempted to complete the machining operation in a mill with 5- axis capability. However, our first attempts at machining the Inconel proved quite We determined the most likely cause of asymmetry in the turbine to be a failure in properly fixturing the component during CNC operations, resulting in the stock piece being not perfectly centered in the lathe chuck. As a result, the turbine blades on one side of the disk were machined approximately 20/1000 in shorter than those on the other side. Due to the difference in the length of the blades, we were forced to either re-machine the rotor or remove 20/1000 in from the overall diameter. We determined that we did not have enough time to machine a second turbine and decided to repair the original. The resulting turbine, prior to balancing, produced substantially less vibration when spun with compressed. However, the alterations to the blade length resulted in a gap between the turbine and the stator housing of 30/1000 in. The specified tolerance between these two parts was 10/1000 in in order to achieve minimal gap losses and maximize efficiency. Although the turbine will be adequate for operation it is not ideal and will suffer from unnecessary gap loss during operation. The completed turbine wheel attached to the shaft can be seen in Figure.



3.8 outer casing and Inlet flange

Perhaps the simplest component to design was the outer casing. A six-inch diameter tube with eight bolt holes placed around the circumference of the compressor side. Bolts passing through these holes secure the inlet flange, outer casing and diffuser into a rigid body and ensure that the spacing between compressor and shroud is maintained. While the compressor end is enclosed by the compressor and inlet shroud assembly, the turbine end is enclosed by the stator housing and an annular endcap. We chose to manufacture the outer housing from a six-inch outer diameter length of 304 stainless steel tubing. The primary challenge during manufacturing was properly holding the tube on a lathe in order to machine the outer and inner diameters. Due to the size and length of the tube, we decided to use a four-jaw chuck to hold it from the inside. We encountered a large amount of deflection and chatter while turning down the outer diameter. To solve this problem, we welded a piece of steel across the inside diameter of one end of the tubing. We then centre drilled the piece of steel and utilized a tailstock and live center to reduce deflection and ensure a uniform surface finish. Following the turning operation on the outer diameter, we flipped the tube and bored the inside to the exact outer radius of the diffuser fins. Once the tube diameters were properly sized, we drilled eight holes around the circumference of the diffuser end and welded an annular endcap to the turbine side. The primary feature of the annular endcap is to allow for the attachment of the nozzle. The outer housing can be seen in Figure.

We also designed and manufactured a simple inlet flange to cover the compressor side of the outer casing and hold the assembly, and engine, together. We designed the flange to fit loosely over the outer casing to allow proper spacing for gasket material. Bolt holes placed around the perimeter of the flange line up with holes on the casing and diffuser. We machined the flange from 7-in diameter 6061 t651 aluminium stock. The machining operation was performed on a HAAS VM-2 utilizing Esprit. We used ½-in end mills to pocket the material and a 3-in face mill in order to give it a flat surface finish. We also drilled the holes on the side using an indexing head and the manual mill. The completed flange can be seen in figure.

Minimizing gap losses and ensuring a tightly sealed engine is crucial to the efficiency of gas turbines. In addition to the turbine, the seal between the outer casing and the flange is an area of concern for gap losses in our engine. Because the flange is bolted to the housing, it is necessary to implement a gasket between the two parts in order to eliminate any leaks. We initially decided to use gasket paper between the two parts but once the engine was assembled, we found that the gasket paper did not provide a reliable seal. We decided that a simpler method might be to seal the gap with a high temperature silicon gasket sealer. The silicon sealer can better fill any small gaps or leaks that might be formed in gasket paper when securing the flange.

3.9 Shaft

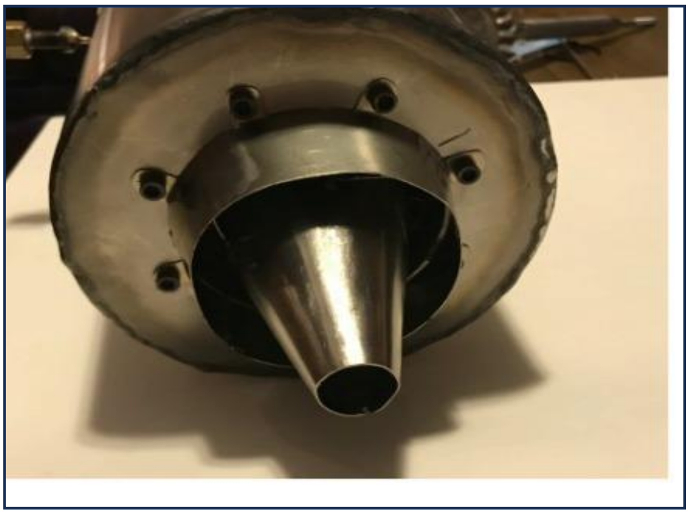
The shaft, made of 316 stainless steel, was cut to about 11.5-in in length and then turned down on a lathe to meet our specifications. The design includes a taper on each side of the shaft intended to decrease stress concentrations and eliminate the sharp edges that might infringe upon lubricant flow through the shaft housing. There are two locator steps/bearing seats that serve to position the bearings on each end, these steps are machined to allow a light press fit upon bearing installation. In order to ensure that the shaft was manufactured to be concentric and as balanced as possible, we utilized an indicator to establish a true rotation in the chuck whenever the workpiece needed to be manipulated. Additionally, during any turning operations the shaft was held by a live centre tailstock to minimize the chances of deflection and inaccuracies. To complete the shaft, we cut left hand threads into each end in order to accommodate the turbine and compressor. The shaft can be seen in Figure.

3.10 Stator and Stator housing

The stator housing was designed to be machined from 316 stainless steel bar stock. The primary purpose of the housing is to hold the stator in place and allow the turbine to rotate at full speed while maintaining the high tolerance necessary for efficiency. We designed a simple geometry which includes a simple thin walled hollow cylinder with a flange on either end. The flanges provide surfaces where the combustion chamber and exhaust nozzle can be attached. On the combustion side, the flange was designed to be welded to the combustion chamber while the nozzle could be attached with bolts feeding through small tabs on the nozzle and into the housing. The stator was machined in the same fashion as the turbine. Once, we machined the stator as a bladed disk, we then installed the disk into the stator housing and welded the blades to the outer walls. The stator housing was machined using 35° and 55° ferrous inserts and a ferrous boring bar to bore out the inner diameter. We then drilled holes on the sides of the housing evenly so that the holes would line up with the blades in order to plug weld the stator inside of the housing. We machined a small lip so that the stator could sit inside of the housing before it was plug welded. The completed stator and stator housing assembly can be seen in Figure.

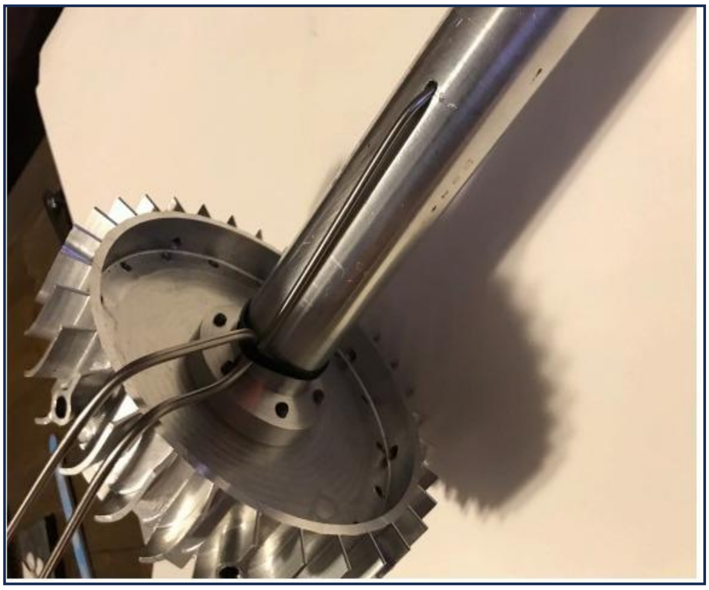
3.11 Exhaust Nozzle

The primary function of an aircraft gas turbine exhaust nozzle is to generate thrust used to propel the aircraft forward his project focused on the design and manufacturing of a self-sustaining engine and we did not prioritize thrust. Our nozzle design objectives were to avoid choked flow and ensure ease of manufacturing. Therefore, we decided to choose a simple converging nozzle design derived from a popular RC jet turbine Our nozzle consists of a short outer cone with a 15-degree taper and a longer yet smaller in diameter inner cone. Additionally, we included eight tabs on the perimeter of the outer cone that allow the nozzle to be bolted to the stator housing and outer casing. All of the components are manufactured from Inconel 718 sheet metal. We used SolidWorks to create a model of the nozzle and generate a 2- dimensional template of the cones which we then transferred to a 0.02-in thick sheet of Inconel. We cut the sheet into two shapes, one for each cone, and tig welded them together. The outside cone was then bolted onto the casing using the tabs. The nozzle can be seen in Figure.



3.12 Bearings, Fuel injection and lubrications

In order to build and operate an engine, it is essential to first consider the bearing, fuel, and lubrication that will keep rotating components moving efficiently. During the first stages of our design process we determined that it would not be feasible to design and build the ball bearings or the fuel and oil pumps. Through research regarding bearings used by RC jet modelers and manufacturers of small gas turbines, we identified a set of bearings that would be capable of withstanding the extreme temperatures and rotational speeds to be experienced in our engine. The bearings we chose are specifically offered, by BOCA Bearing, for miniature jet turbines, they are stainless steel/ceramic hybrid angular contact bearings capable of withstanding RPM up to 100,000 with proper lubrication. Originally, the combustion chamber was designed specifically to accommodate liquid fuels through the use of the vaporization tubes. However, it became apparent later in the design process that we would be unable to purchase and assemble a fuel pump and throttle system within the allotted timeframe and budget. However, our engine is capable of running on multiple fuels, both liquid and gaseous. Therefore, we decided to run the engine on gaseous fuel in order to eliminate the need for a fuel pump and achieve throttling through the use of a valve. The theoretical minimal fuel consumption calculation using propane can be seen in Appendix C. In order to ensure that the bearings would not fail at high rotational speeds and temperatures during operation, we incorporated a bearing lubrication system into our design. The system consists of two ¼in stainless steel tubes entering through the outer casing, running along the blackface of the diffuser, and entering the shaft housing at the location of each bearing. We also purchased an oil pump to push oil from a reservoir into the engine. The lubrication design can be seen in Figure.



Small assembly of compressor diffuser axial and turbine

4.0 conclusions and recommendations

Over the course of this project we successfully designed and manufactured all twelve of the components outlined in Chapter 1 that constitute our jet engine. Additionally, we successfully assembled the engine. Figure 22 at the end of this section show the nozzle and compressor ends of the dry fit assembly. However, due to substantial manufacturing setbacks we were unable to test the engine before the deadline. These setbacks included the failed Inconel turbine and steel turbine asymmetry. In order to complete the manufacturing aspect of our project, we postponed our plans to manufacture a test stand, balance the shaft assembly, create a throttle mechanism, and seal the engine for operation. In order to operate our engine by the end of this academic year, we plan to continue working towards creating the necessary components. We have contacted a local company specializing in balancing rotating components and they agreed to balance our shaft assembly. Creating a throttle mechanism for our engine has been simplified by the use of gaseous fuel. We plan to use an adjustable valve that controls the flow of propane therefore increasing or decreasing throttle. To ensure our engine is properly sealed, we will abandon the use of gasket paper and employ a high temperature silicon gasket sealer around the flange during final assembly. Finally, we plan to construct a simple static engine stand that will support the engine during operation and safeguard operators in the event of engine failure. Despite our setbacks and failure to operate the engine in the given timeframe, we are working to complete the engine before the end of this academic year order to provide assistance to any future project groups interested in manufacturing their own miniature gas turbine, we have provided a list of recommendations that will expedite the design and manufacturing process and possibly facilitate the integration of instrumentation, thrust considerations, and efficiency into their design.

- We recommend avoiding super alloys, like Inconel 718, when constructing a turbine unless the group has access to proper CNC tooling and equipment and experience machining with other similar alloys
- We recommend that when selecting or manufacturing a compressor, ensure a CAD model is available. A CAD model enables the use of computer software to quickly design a compressor inlet shroud that meets tolerances necessary for engine efficiency.
- We recommend further research into flange design in order to create a flange that can integrate gasket material and ensure a proper, reliable seal.

Reflecting on the process we have gone through during the design and manufacturing of our engine has led us to realize the difficulties of designing and building an original engine. Many design advancements in gas turbines have been developed through experimentation and iteration. The design of any component manufactured during this project could be challenging enough to warrant a project of equal magnitude. Years of research and development could be spent designing a turbine blade or new combustion chamber. Additionally, the volume of research and information regarding gas turbines is simply immense and often difficult to navigate. Considering these factors, it becomes evident that our project was quite ambitious. However, through our struggles, we gained first-hand knowledge of gas turbines and the challenges faced during their design and manufacturing.

References

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