Thermodynamics Demonstration Unit 1B
Power Generating Turbojet Engine

EGR 486C-02

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Table of Contents

List of Tables and Figures

Tables

Figures

1.0 Background

1.1 Introduction

The thermodynamic Brayton cycle has wide ranging applications from power plants to jet engines. Although courses of thermodynamics provide the necessary information for a Brayton cycle, they lack the physical demonstrations to portray the inner workings with respect to a jet engine. The Brayton cycle works in four stages: compression of the working fluid, introduction of heat within the heat exchanger, isentropic expansion through the turbine to produce work, then finally passes through another heat exchanger before starting again in the compressor. It was determined by the team that a power generating turbojet engine is a simple concept that illustrates aspects of introductory thermodynamics.

1.2 Project Description

The team was given the task of designing and building an educational model of the Brayton cycle for use in thermodynamic classes. The model is to demonstrate the compression, expansion, and heat addition principles shown in a classic Brayton cycle in a thermodynamic class. The ultimate goal is to collect real time data to display on T-s and P-v diagrams while the cycle is running. Through iterations of the project, the scope has been narrowed down to a power generating turbojet engine that will convert rotational energy into electrical energy to illustrate power output.

2.0 Requirements

Through the process of client meetings and customer interviews, the team was able to relate the problem statement for the project to customer needs. By determining customer needs, the team assembled engineering requirements to demonstrate the critical components of the project.

2.1 Customer Requirements

Based on the client suggestion, we met with the thermodynamic professors (Dr. Mazumdar, Dr. Nelson, Dr. Wade, and Prof. Willy) at Northern Arizona University to collect the customer requirements. The Responses of requirements can be seen in Table 1.

Table 1: Customer Requirements

Customer Requirements	Weighting	Justification
Collect Data	5	The fundamental principles behind teaching the Brayton Cycle to future students
Safety	5	No damage or deterioration of model over time to ensure functionality
Functionality	3	Must be operational for a maximum of 15 minutes to simulate a Brayton Cycle
Rigorous Design	4	Team designed blades, casing, and data acquisition
Analysis	5	Turbomachinery design and Brayton Cycle
Cost	3	Maintain low cost for entirety of project
Visibility	4	To visually illustrate the processes of a Brayton Cycle

2.2 Engineering Requirements

The team's engineering requirements can be found in table 2. The team collected the customer requirements information from the client and customers to determine the required engineering requirements.

Table 2: Engineering Requirements

Engineering Requirements	Target	Units	Justification
Work Output	20 Watt	$Watt$	Production of power from turbines will turn on a light bulb connected to the system.
Aerodynamic	>.3	C_d	Minimizing aerodynamic drag will increase the power produced from turbines
Thermal Capacity	100	K/m^2	Implementation of a heat exchanger, will provide the data for interactive graphs
Volume	<.5	m^3	Constant volume measurements for each process of cycle is required for P-v diagrams
Data Acquisition	Pressure and Temperature	Pa, K	To create a realtime chart for T-s & P-v diagrams to simulate a Brayton Cycle

2.3 Testing Procedure

The initial testing procedures will include turning on a compressor to generate pressures to start the system. After the air is properly compressed, the operator will release the air through two tubes. The first tube will be pointing the front of the compressor section and the other tube will connect to the heat exchanger before the turbine section. Air will enter both sections and turn the blades as designed. The spinning shaft will be spinning around a generator that will turn the rotational energy into electrical energy to power an LED light strip. The LED light strip will indicate to the students that work is produced from the system.

2.4 House of Quality

House of Quality can be seen in Table 3. The house of quality is a tool for understanding the relationship between the customer requirements and the engineering requirements. The QFD also allows us to understand how the design can be improved by knowing the most detail on our design. Based on the QFD we can decide or determine the most effective component in order to design an educational high bypass turbofan.

Table 3: House of Quality

Brayton Cycle Educational Model											
	Work output (more is better)			+	-	+	0	+	+	+	+
	aerodynamic	+		0	+	0	-	+	+	0	0
	thermal capacity (more is better)	+	0		-		-	0	0	+	
	isentropic efficiency (more is better)	+	+	+	0	+	0	+	0	+	+
	Volume (less is better)	-	+	-		0	0	0	0	0	-
	Data Acquisition	+	0	0	0		0	0	0	0	0
	opacity (less is better)	0	0	-	+	0		0	0	0	-
Customer Requirements	Weighting	Power output	aerodynamic	Thermal Capacity	Volume	Data Acquisition	opacity	$\eta_{thermal}$	$\eta_{proulsive}$	$\eta_{thermal}$	$\eta_{isentropic}$
Collect Data	5	2	1	3	1	3	2	3	3	3	3
Safety (more is better)	5	2	1	3	3	1	1	3	3	3	3
Functionality	3	3	3	1	2	2	1	1	1	1	1
Rigorous Design	4	3	3	2	2	3	1	2	2	2	2
Analysis of Brayton cycle	5	2	1	2	1	3	1	2	2	2	2
Cost (less is better)	3	3	2	3	3	3	1	3	3	3	3
Visibility (more is better)	4	1	2	2	2	1	3	2	2	2	2
Technical Requirement Units		[W]	C_d	[K/m^2]	[m$^{3]}$	[K],[Pa],[N]	[%]	[%]	[%]	[%]	[K]
Technical Requirement Targets		20 Watt	0.4	756	<.5	378	<20%	>80%	>80%	>80%	>80%
Absolute Technical Importance		64	50	68	56	66	42	68	68	68	68
Relative Technical Importance		10.3559871	8.09061489	11.00323625	9.06148867	10.6796117	6.7961165	11.0032362	11.003	11.003	11.003

3.0 Existing Designs

An existing design that the team has based designs around is the Rolls-Royce Trent 556 [1]. Modeling the existing Rolls-Royce engine to a working 3D printed model has been done through sizing to simulate an operational turbojet. Components will be tested by blowing air, as the working fluid, through the model at different velocities and measuring the velocities, temperatures, and pressures. Individual components will be tested and compared to the benchmark throughout the design process. The pressures after the compressor will be measured with a pressure transducer displayed in the team's budget. The temperatures will be measured using thermocouples as to record the exact temperatures at a specific time. The power generation will be tested through means of measuring the rotational rotational speed of the shaft.

3.1 Design Research
Existing models that simulate the Brayton Cycle process through turbojets have been researched to find optimal solutions to the subsystem levels. Utilizing the existing model designs as benchmarking our designs.

Further research was performed to create the top level systems. Each top level system: rotor blade design, data acquisition, and casing design was broken down into further subsystems to create unique designs for specific sections of the project.

3.2 System Level
To design an operational power generating turbojet engine that is educational, the team has allocated research into the rotor blade design, data acquisition, and casing design. The purpose of these systems is to finalize design options through the means of a pugh chart. Each of the top level systems have been analyzed provide background along with related associations to the project.

3.2.1 Rotor Blade Design
Current rotor blade designs have been generated through many iterations to fit any and all situations. Utilizing Airfoil Tools [2], it is possible to examine blades that meet the speed and Reynolds numbers. For the project, there are two rotor blades in question: axial compressors, and axial turbines. To analyze the performance and outputs of the rotor blades, it is critical to apply the Euler Turbomachinery equations for the work output potential of the system [3].

Current rotor blade designs are complex and arguably the most important factor of the modern jet engine. The compressor blades are designed to slow and compress the incoming working fluid to a calculated internal pressure. To achieve this, the blades have a twisted contour design that helps direct the fluid flow towards the following compressor blades more efficiently than simply a blade with no twisted contour. This transfers the fluid's kinetic energy into usable potential energy. Following the compressor and combustion chamber, the turbine blades are used to direct the working fluid out of the system, providing thrust. The turbine blades are designed similarly to compressor blades, however turbine blades are designed with a more defined curvature to propel the working fluid out of the system at a higher velocity than it entered with.

3.2.2 Data Acquisition
From the problem statement set by the client, educating future engineering students on the principles of thermodynamics, data acquisition is the top level system responsible for educational purposes. It was determined that the project will display four parameters of the Brayton Cycle: temperature, entropy, pressure, and work output. Having two teams work on the

same problem statement, it was determined that the teams will share the data acquisition for cost.

Pressure taps must been designed and standardized for the implementation of both projects. Demonstration of the pressure will be visible with a series of manometers to display the static and dynamic pressures. Thermocouples are necessary to generate a working T-s and P-v diagrams.

Current technology used in acquiring pressure is pitot-static tubes in flying aircraft, and manometers in wind tunnels. For temperature data acquisition, thermocouples are used in many applications to evaluate exact locations of temperature

3.2.3 Casing Design

Current designs for a High Bypass Turbofan include a volume reduction for the combustion chamber to increase pressure and temperature. Applying current design applications of a high bypass turbofan is unrealistic in the project, due to the high precision of manufacturing and high temperatures. Due to the constraints of material selection and maximum temperatures, reducing volume in the heat exchanger section does not yield better results.

3.3 Functional Decomposition

3.3.1 Black Box Model

The black box model for the educational high bypass turbofan is important to identify all the materials, energies, and signals that are critical for the unit to produce power. Implementation of each of the customer requirements in the black box model illustrates the importance of how the team plans to incorporate data acquisition to achieve an educational model. Figure 1 shows the team's black box model.

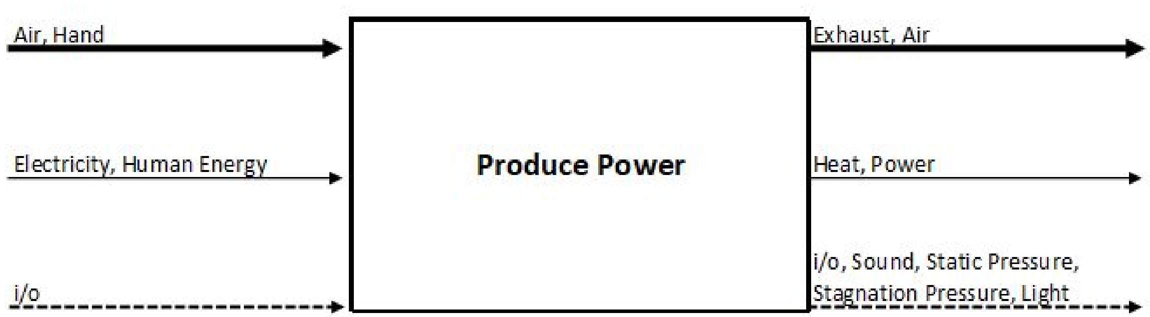


Figure 1: Black Box Model

3.3.2 Project Decomposition

A turbofan process was created using a functional flowchart to illustrate the processes involved throughout the model in order to generate a visual demonstration of P-v diagrams as well as temperature locations. Figure 2 shows all the work and heat flows along the entire turbojet engine.

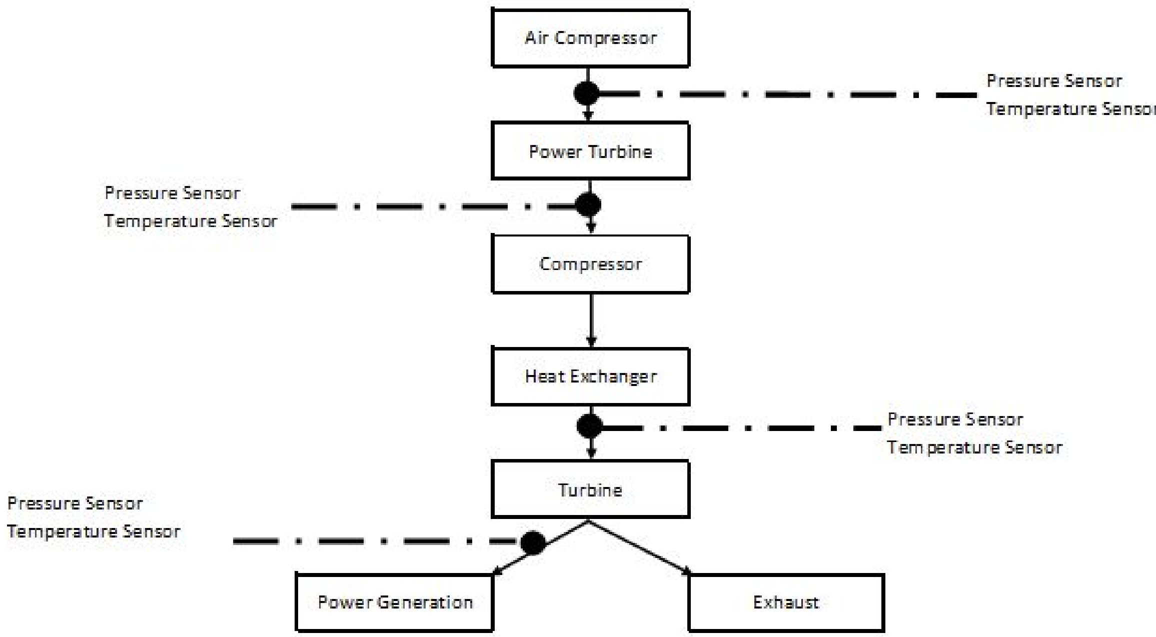


Figure 2: Project Decomposition

3.4 System Sublevel

3.4.1 Rotor Blade Component Research

To further develop an operational Brayton Cycle research was required to justify decisions and implement design changes. In this section, previous research is compiled that was useful in the final design selection.

3.4.1.1 Chord Width

The chord of the fan blade has and impact on the efficiency, weight and cost of the engine. Figure 3 shows the difference between clappered blades and a wide-chord blade. Long thin blades are lighter but require a clappered in the middle of the blade to prevent blade deformation. Shock waves form around the clappers causing a reduction in efficiency. Wide chord fan blades are more efficient but heavier and more expensive. The added weight of bigger blade requires more expensive hollow titanium blades.

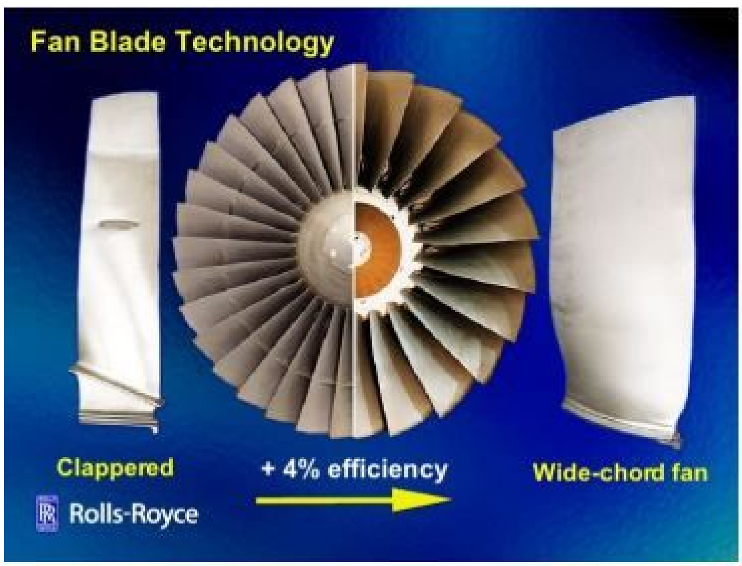


Figure 3: Fan Blade Technologies [3]

3.4.1.2 Angle of attack

The angle of attack is defined as the angle between the chord line and the direction the flow is moving. Figure 4 shows the visualization of the topic.

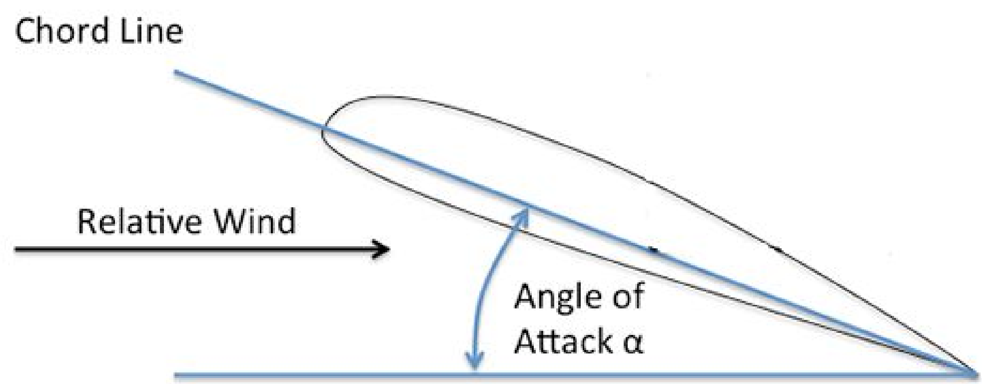


Figure 4: Angle of Attack for Rotor Blade Design [5]

The angle of attack is used in rotor blades to direct the fluid flow to either the next blade or to the next section of the engine. For the compressor blades, the angle of attack of the first blade is relatively large in order to slow down the fluid flow and direct it to the next blade. The following blade will not have as extreme of an angle of attack, but will have the same function of the first blade: to continually slow down the fluid in order to increase the pressure. Depending on the desired compression ratio, the number of compressor blades will be variable to reach the ratio. Following the heat exchanger, the turbine blades serve a similar purpose as the compressor blades. The turbine blades are designed with relatively small angle of attack, but instead with a large blade curvature. How curvature of the blade affects the fluid flow is discussed further in the following curvature section.

3.4.1.3 Normal force relative to fluid speed

The normal force created from the resulting fluid flow is considered to be the lift. Lift is usually related to airfoils with designing airplanes, but lift correlates with the angular velocity for rotor blades. Figure 5 Without the rotor spinning, the fluid will not be moving as designed, therefore not being compressed properly. With the rotors spinning, the fluid is transitioning from linear movements to spinning around the shaft, which further compresses the fluid as desired.

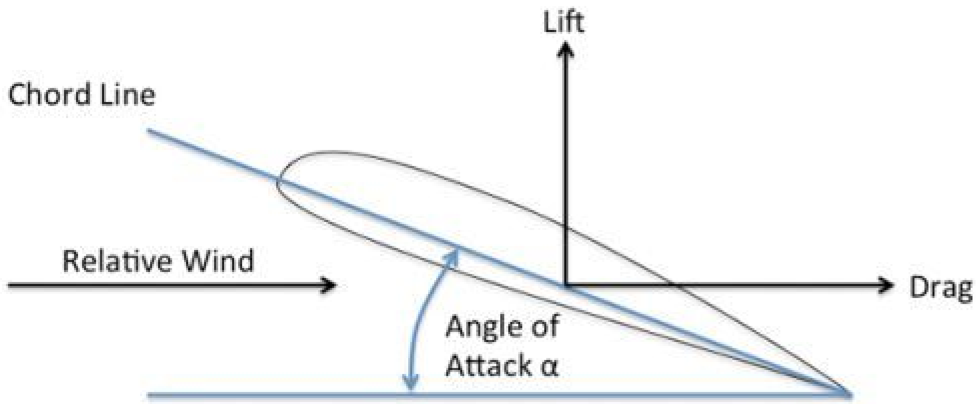


Figure 5: Lift for Rotor Blade Design [5]

3.4.1.4 Curvature

The curvature of compressor or turbine blades dictates where the fluid is going to be directed. Similar to the angle of attack, the curvature has a large influence on how well the fluid is compressed in the initial compressor blades and how quickly the fluid exits the turbine. When the fluid comes into contact with the first turbine blade, the highly pressurized fluid will start to convert the stored potential energy and convert it back to kinetic energy. The curvature of the blades will dictate the velocity and direction of the exiting fluid. Ideally, the velocity of the fluid leaving the turbine is the work out of the system. Therefore, the design of curvature for the turbine blades has the largest influence of fluid speed and overall efficiency of the system. The velocity exiting the system must be greater than the velocity of the fluid moving into the system, i.e. work out must be greater than work in. Figure 6 displays the different designs for curvature of turbine rotor blades.

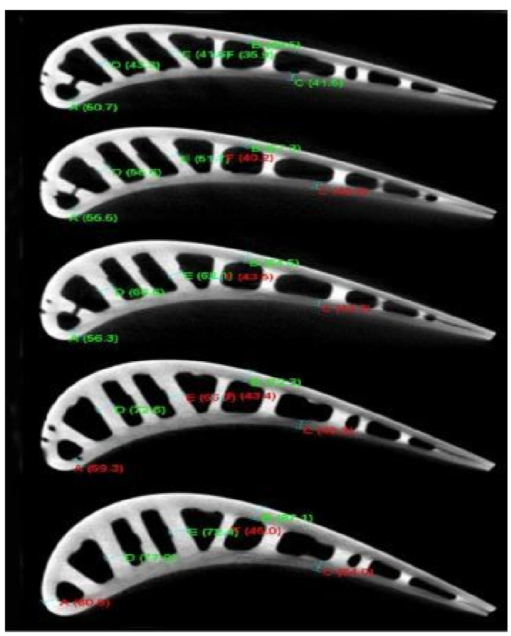


Figure 6: Curvature for Different Rotor Blade Design [6]

3.4.2 Data Acquisition

3.4.2.1 Pressure Acquisition

Pressures must be acquired through four critical stages to generate a P-V diagram. Pitot-static tubes can be used at the inlet and outlet of the turbofan to calculate the static and stagnation pressure to calculate the relative velocity within the high bypass area. Flexible pitot static tubes can be implemented at the desired locations and held in place via rubber gaskets and sealant. Data acquired will be digital for the pitot-static tubes, that is directly connected to the selected data acquisition software.

3.4.2.2 Temperature Acquisition

Similarly to the pressure, temperature must be measured at critical stages of the turbofan process to generate a T-s diagram. Thermocouples will be placed at the inlet, outlet, heat exchanger, and high bypass area. Each of the temperature locations is identical to pressure locations, therefore the same drilled holes that house the pressure sensors will also house thermocouples.

3.4.2.3 Data Acquisition Software

To create a real time P-v and T-s diagram, LabView has been selected to acquire the pressure and temperature data. Alternative software such as Matlab Simulink, and Excel can be used to cost effectively generate plots not in real time. The team proposes to illustrate the power generated through the lightbulb, pressure at each state, temperature at each state, and the volume for each state on a electronic display.

3.4.3 Casing Design

3.4.3.1 Area Reduction Designs

To accurately demonstrate the inner workings of a high bypass turbofan, the area of the heat exchanger must be reduced to increase pressure while introducing additional heat to the system. Due to material and size constraints, reducing work space is difficult to design and construct to safely introduce a heat source. Designing a reduced heat exchanger area will require additional 3D printed supports that have viewing areas for educational purposes.

3.4.3.2 Straight Area Low Bypass

By maintaining the same inlet area throughout the entire turbo fan, simplifies the overall design while increasing the difficulty of implementing more heat. Constructing a straight area low bypass simplifies the visibility for the internal workings of a turbo fan.

3.4.3.3 Heating Element Introduction

By implementing a heating element to the turbofan system, more work will be produced. Although the addition of heat into the system will not produce a higher thrust yield, it will simulate realistic conditions to generate a T-s diagram. Research was done for the implementation of a heating element, and was determined that a hot wire foam cutter is the simplest and more cost effective means to increase temperature.

4.0 Designs Considered

Rotor Blade Design 1-
Using one compressor blade and one turbine blade is ideal in design simplicity, but the resulting efficiency will not be relevant. The air moving into the system will not have slowed down and compressed enough to get relevant compression ratios. The single turbine blade will not be able to convert the potential energy after the compressor into relevant kinetic energy. Essentially the work out will be similar to the work in, not creating ideal efficiencies. Throughout the project, the design has gone through several iterations while remaining a functioning Brayton Cycle. Figure 7 shows a 1:1 compressor to turbine ratio.

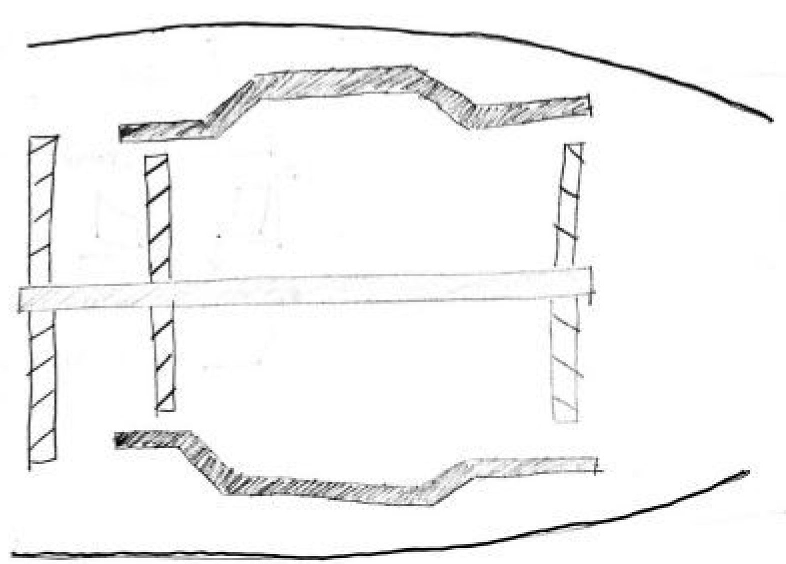


Figure 7: 1:1 Compressor to Turbine Ratio

Rotor Blade Design 2-

Designing the turbofan to have a total of four compressors and three turbines will yield a higher compression ratio prior to the introduction of heat. Figure 8 illustrates that a higher number of compressor blades will increase pressure. The increased number of turbine blades will convert the potential energy into kinetic energy more efficiently, therefore increasing the efficiency of the overall system.

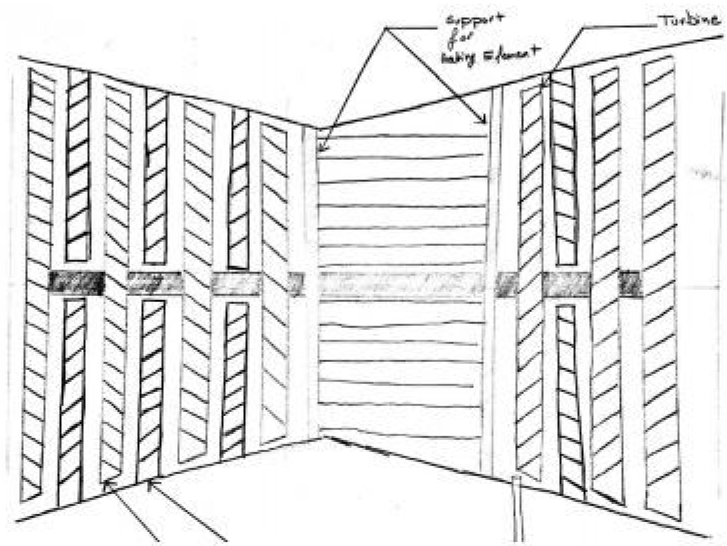


Figure 8: 4:3 Compressor to Turbine Ratio

Casing Design 1-

Constant area for the heat exchanger is the simplest of the designs for the casing, as seen in Figure 9. A disadvantage of this design is it's failure to educationally represent the true functions of a working turbo fan. Although the decrease in area for the heat exchanger will not produce better results for the project, it does not accurately represent a working high bypass turbo fan.

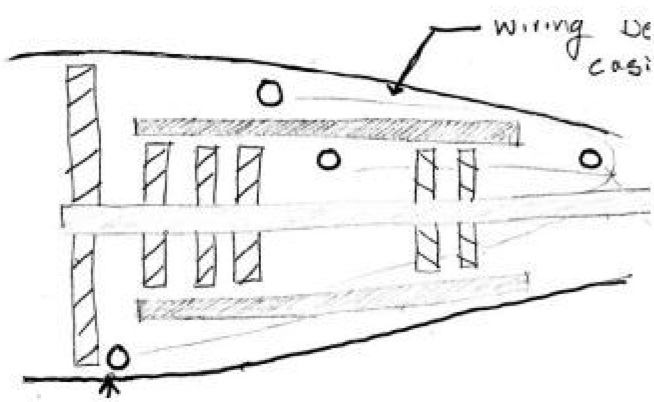


Figure 9: Constant Area for Heat Exchanger

Casing Design 2-
Increasing the area of the heat exchanger is useful for the simplifying the addition of the heating element, as seen in Figure 10. Although the increase of area is beneficial for construction simplicity, it does not accurately portray the real inner workings of a combustion chamber. In an operating high bypass turbofan, the decrease of area is useful to increase the pressure and temperatures necessary to produce thrust.

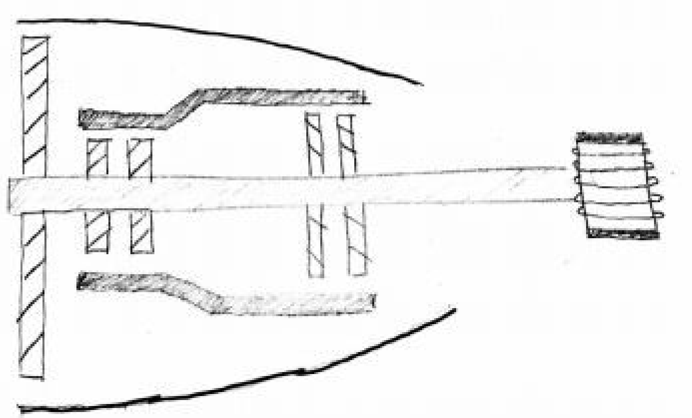


Figure 10: Increased Area for Heat Exchanger

Casing Design 3-
Decreasing the area for the heat exchanger is the most realistic model for illustrating the increase of pressure and temperature in a high bypass turbofan. Although the area reduction accurately portrays a working turbofan, it makes the installation of the heat exchanger more difficult as well as more difficult to design the casing. Figure 11 shows a decreasing area for the heat exchanger.

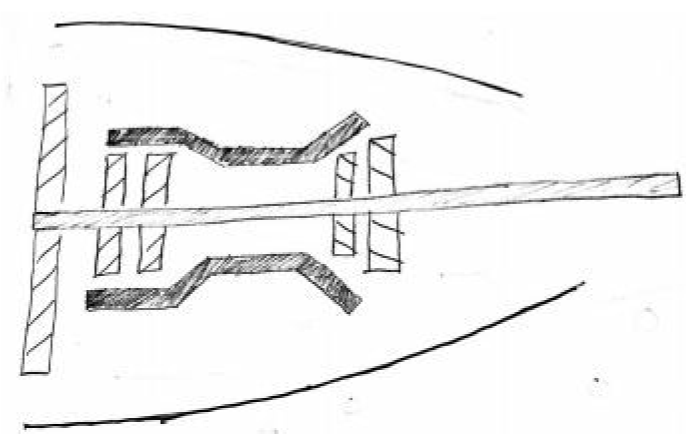


Figure 11: Decreased Area for Heat Exchanger

Pressure Acquisition 1-

Flexible pitot-static tubes have been researched and found to be simple to implement into the system through planned holes in the casing. Having a system of two pitot static tubes measuring the pressures of the heat exchanger and the high bypass area, data for velocity can be calculated through dynamic pressure. Figure 12 shows a typical pitot static tube.

Figure 12: Pitot Static Tube [7]

Pressure Acquisition 2-

Applying an inclined manometer at the inlet and outlet of the turbofan will simulate stage 1 and 4 of the Brayton cycle. Having a manometer at the inlet and outlet adds to the simplicity of set up for demonstration purposes. Figure 13 shows a typical Manometer.

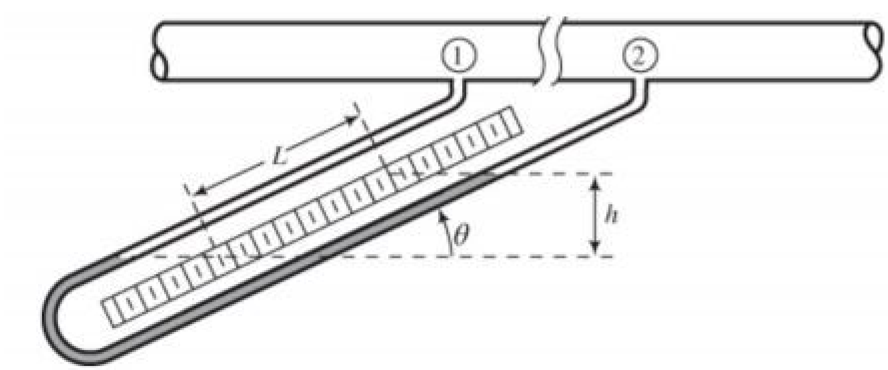


Figure 13: Manometer [8]

Heat Exchanger-

The heat exchanger will have a collar heater to add heat into the system, simulating combustion. By introducing heat to the system, the internal temperature will rise and assist in compressing the air. This will generate a higher work output, which is the goal of the project.

Temperature Acquisition-
Located at the same places as the pressure sensors, the thermocouples will be at each stage of the Brayton Cycle. Measuring the temperature difference is useful to illustrate the cause and effects of a heat exchanger in the Brayton Cycle process. Figure 14 shows the typical thermocouple.

Figure 14: Thermocouple [9]

Data Collection Software-
Through the means of data collection, the team hopes to illustrate the educational principles of thermodynamics through pressure, volume, temperature, and power produced. Power will be displayed on a screen as well as being illustrated through a generator to power a light bulb. Although data collection software research has been limited, the team is focusing on illustrating each pressure and temperature for the stages of a Brayton Cycle.

5.0 Design Selected

In this section the various design iterations are reviewed and discussed to demonstrate the design process for the project. By breaking the project into three main components, it is possible to work on a parametric solution to each section. Each component has an analysis performed, excluding the heat exchanger for teaming reasons, the calculations for the sections are explained in this section.

5.1 Rationale for Design Selection

Different designs which include a potential gearbox and strain gauges for thrust measurements were considered throughout the concept generation phase. Below in Table 4 is the pugh chart which categorizes each criteria against designs. For educational purposes, instead of using pitot static tubes or strain gauges the team decided to use pressure transducers and thermocouples in order to record real time data with software.

Table 4 : Pugh chart

		Stator Blade on casing	Stator Blade on shaft	Gear box	No Gear box	Pitot Static Tubes	Strain Gauges
		Concept 1	Concept 2	Concept 5	Concept 6	Concept 7	Concept 8
Criteria	Weight						
Work Output	5	S	S	+	-	S	S
Isentropic Efficiency	3	+	-	+	-	+	-
Thermal Capacity	2	S	S	S	S	S	S
Volume	3	S	S	+	-	S	S
Data acquisition	5	S	S	S	S	S	S
Cost	3	S	S	+	-	-	+
Aerodynamic	4	S	S	-	+	-	+
Internal Velocity	3	S	S	-	+	S	S

5.1.1 Compressor

Designing the compressor blades includes using the assumptions as air is the working fluid, the Reynold's number is kept below 4000 (turbulent), uniform properties at inlet, and the material used to print the blades will the be the standard material at Cline library and the RapidLab. Applying these assumptions leads to inlet properties of:

1. Density = .0586 lb/ft^3
2. Inlet velocity = 20 ft/s
3. Length of blade = .5 in
4. Viscosity = 1.63×10^{-4} $lb_f \cdot s/ft^2$
5. Reynold's number = 3600 (transition region)
6. Temperature = 70°F
7. Inlet area = 0.19635 ft^2
8. Flow rate = 3.923 ft^3/s
9. Mass flow rate = .23 lb/s

The main equation used to find the angular velocity of the shaft, and ultimately the power output from the turbine, is shown in equation 1.

$$\tan^{-1}(1/\phi) = \alpha \qquad \text{(Eqn. 1)}$$

Where:

$\phi = U/V$

U = inlet velocity of air

V = Tangential velocity of the blade

α = Angle of attack (assumed 60°, 45°, 30°, and 15°)

These calculations led to the design of the compressor blades with specific angles of attack, at 60° to 15°. These are shown in the figures below. Figures 15 and 16 show the current iteration of compressor blades. All of the equations used for the compressor section can be seen in the appendix.

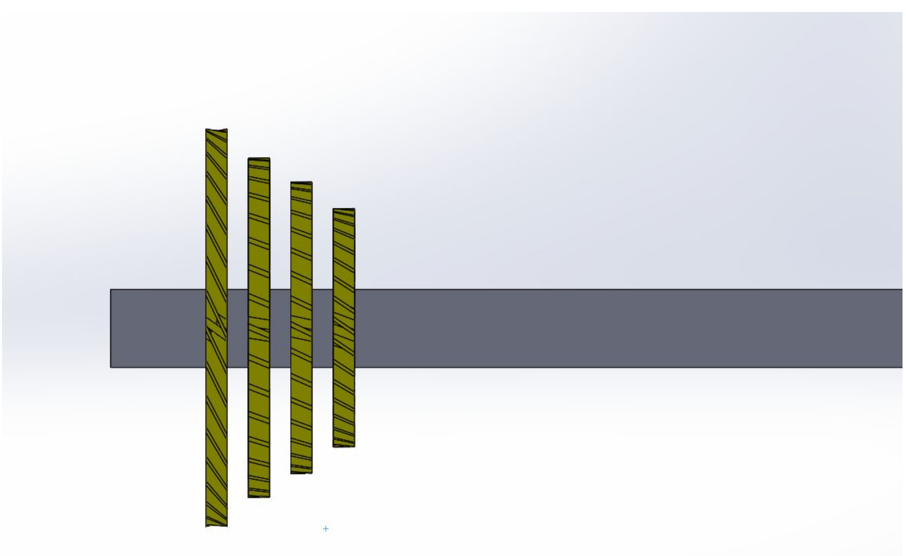


Figure 15: Side view Compressor

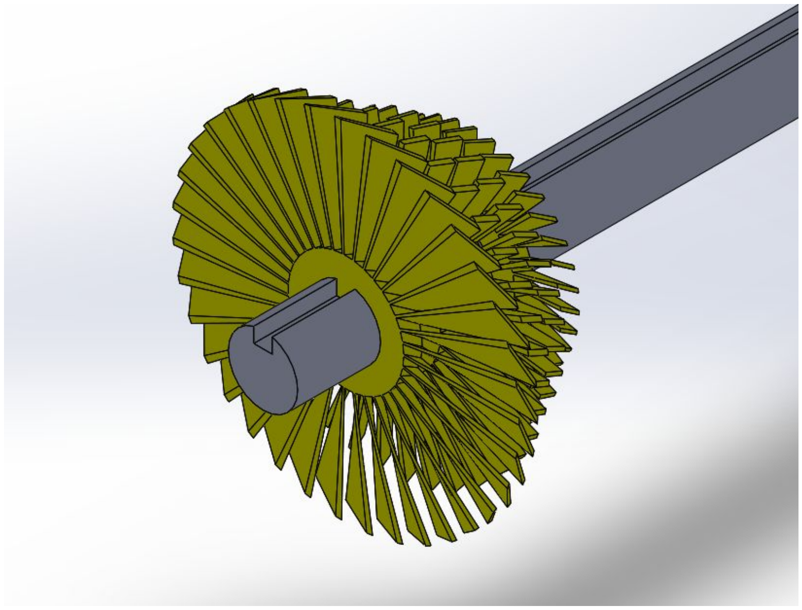


Figure 16: Compressor Cascade

5.1.2 Heating Chamber

The heating chambers purpose is to increase the temperature of the working fluids, while providing housing for the heating element and structural support for compressor and turbine section. Utilizing a heating band, figure 18, housed in the center of the chamber, there are two proposed holes that allow access of the wiring.

Figure 17: Heating band [10]

Another element of the heating chamber is to provide structural support for the turbine & stator section, while providing the compression area reduction for the compressor blades. While providing area reduction, the heating chamber will house the compressor section. Mimicking the peg assembly on the stator sections, the heating chamber will lock with the stator and turbine housing. Figure 18 and 19 show different angles of the Heating Chamber.

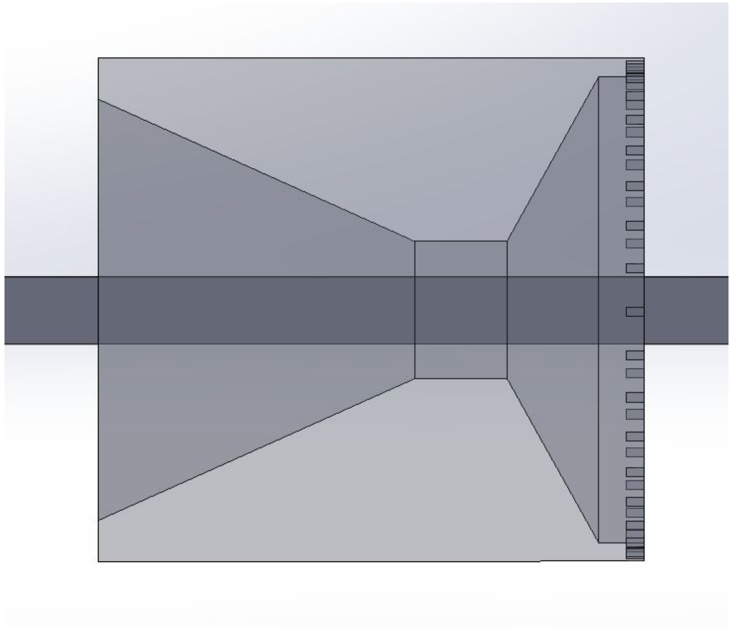


Figure 18: Side view of Heating Chamber

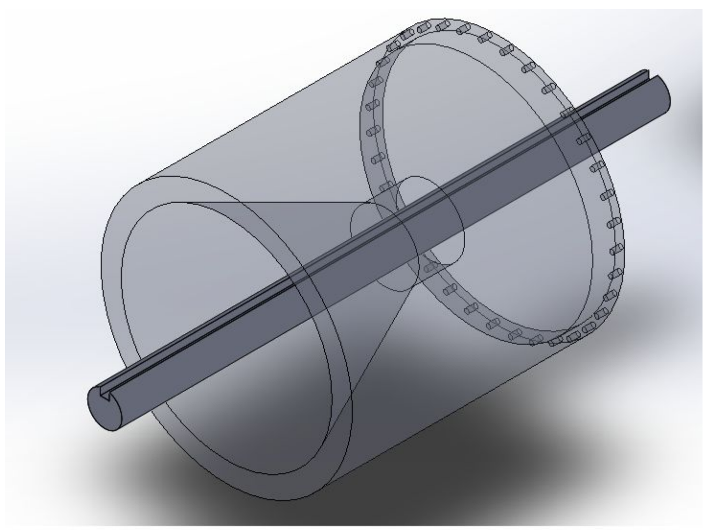


Figure 19: Heating Chamber Housing

5.1.3 Turbine

Designing the Turbine section included an analysis of the necessary power output and the inlet velocities. To perform the calculations to find the optimal angles of the turbine blades, the Euler Turbomachinery equation was used.

Initial properties for the turbine analysis began with rough assumptions of how the model will operate. Inlet properties for the Turbine section are related to the outlet properties of the compressor and heat exchanger. Inlet velocity occurs from the radially placed air compressor that allows for rotation of the blade sections.

Table 5: Turbine Dimensions

Parameter	Dimensions
Inner Diameter	0.5 ft
Outer Diameter	.0625 ft
Rotational Speed	672 rad/s
Inlet Velocity	21 ft/s
Outlet Velocity (End of Staging velocity)	17 ft/s
Speed Decrease per stage	-1 ft/s
Blade Thickness	.0417 ft
Chord Length	.0668 ft
Inlet Blade angle	1°
Outlet Blade angle	23°
Target Power Output	20 Watt
Theoretical Power Output	21.85 Watt

Table 6: Turbine Section Properties

Property	Units
Density	0.00221 slug/ft^3 at 100° F
Dynamic Viscosity	3.96 x 10^{-7} lb$_f$ · s/ft^2 at 100° F
Inner Diameter Reynolds	1.56 x 10^4
Outer Diameter Reynolds	1.17 x 10^5
Inlet Temperature	100° F
Mass Flow Rate	4.04 x 10^{-5} slug/s

Volumetric Flow Rate	0.0177 ft^3/s

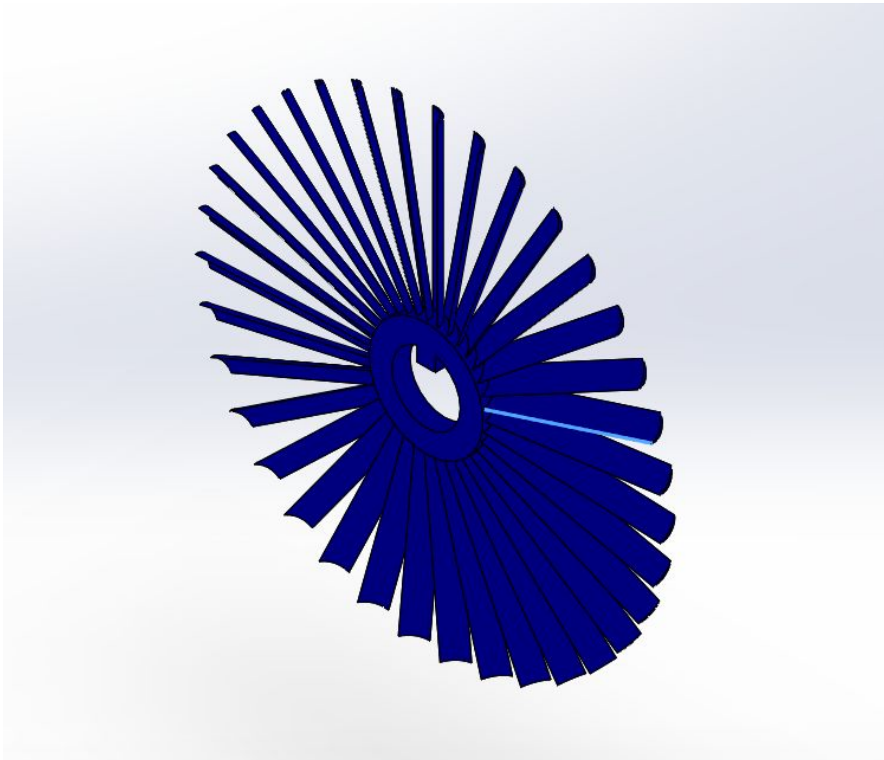


Figure 20: Turbine Blade

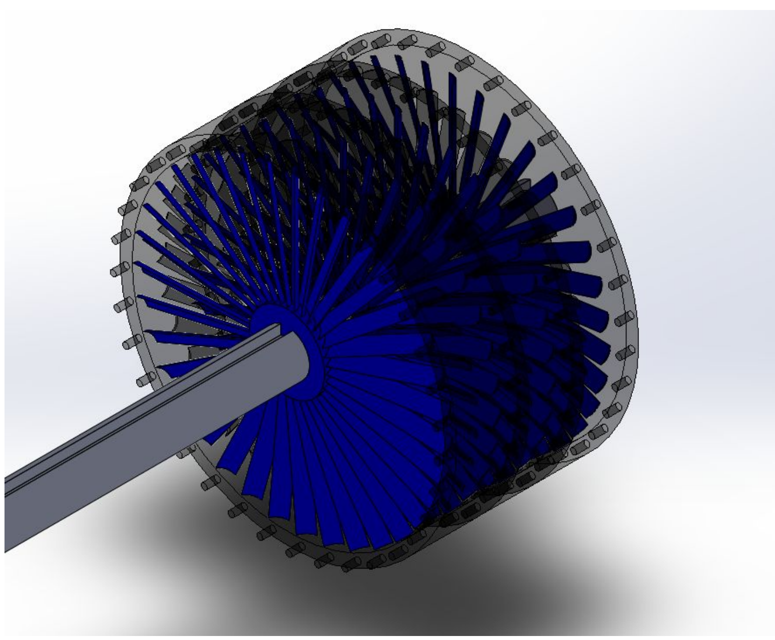


Figure 21: Turbine & Stator Staging

Defining the Reynolds number for the Turbine section was split into different parameters to calculate the rotational speed affect and the Reynolds over the chord length. The change of diameter for the blade length will affect the Reynolds number for elements of the blade. Inner diameter and outer of the blade was determined.

$$Re = \frac{0.00229\ slug/ft^3 \cdot 21\ ft/s \cdot 0.802\ ft}{3.85\ x\ 10^{-7} lb_f s/ft^2} = 1 \text{ x } 10^5 \quad \text{(Eqn. 1)}$$

$$\text{Inner Diameter: } Re = \frac{0.00229\ slug/ft^3 \cdot 672\ rad/s \cdot (.0039\ ft)^2}{3.85\ x\ 10^{-7} lb_f s/ft^2} = 1.56 \text{ x } 10^4 \quad \text{(Eqn. 2)}$$

$$\text{Outer Diameter: } Re = \frac{0.00229\ slug/ft^3 \cdot 672\ rad/s \cdot (.25\ ft)^2}{3.85\ x\ 10^{-7} lb_f s/ft^2} = 1.25 \text{ x } 10^5 \quad \text{(Eqn. 2)}$$

After calculating the Reynolds number, a spreadsheet was made to analyze inlet velocities, angle of attack, and power output. These calculations were performed via the Euler Turbomachinery equations that produce the work output depending on the change of rotational speed and angles. Utilizing the equations for the Euler turbomachinery, a inlet velocity was chosen to lock in the rotational speed with a selected diameter.

Calculating the tangential velocities from a range of angles and inlet/outlet velocities. Figure [X] shows how the power output increases from a increase of blade pitch assuming a set velocity. To illustrate the Euler Turbomachinery equations with a set of four turbines, it was determined that the power output would be 21.85 Watts.

Power for Turbine 1

$$W = 0.00004\ slug/s \cdot (20\ ft/s \cdot 19.83\ ft/s - 21\ ft/s \cdot 20.83\ ft/s) = 2.24 \text{ Watts} \quad \text{(Eqn. 6)}$$

Power for Turbine 2

$$W = 0.00004\ slug/s \cdot (19\ ft/s \cdot 18.83\ ft/s - 20\ ft/s \cdot 19.82\ ft/s) = 0.0058 \text{ Watts} \quad \text{(Eqn. 6)}$$

Power for Turbine 3

$$W = 0.00004\ slug/s \cdot (18\ ft/s \cdot 17.83\ ft/s - 19\ ft/s \cdot 18.83\ ft/s) = 2.016 \text{ Watts} \quad \text{(Eqn. 6)}$$

Power for Turbine 4

$$W = 0.00004\ slug/s \cdot (17\ ft/s \cdot -0.16\ ft/s - 18\ ft/s \cdot 17.83\ ft/s) = 17.6 \text{ Watts} \quad \text{(Eqn. 6)}$$

Overall Power

2.24 Watts + 0.0058 Watts + 2.016 Watts + 17.6 Watts = 21.85 Watts

5.1.4 Stator Section

The purpose of the stator section is to redirect the airflow as well as provide the structural support for the outer casing and the shaft. To design a stator section that satisfies these requirements, the team decided that it was also crucial to have a modulated system that allowed for the stator sections to house the turbine blades as well as interlock with each other and the heating chamber.

Within the center of the stator section, a ball bearing allowing the shaft to rotate freely while providing structural support.

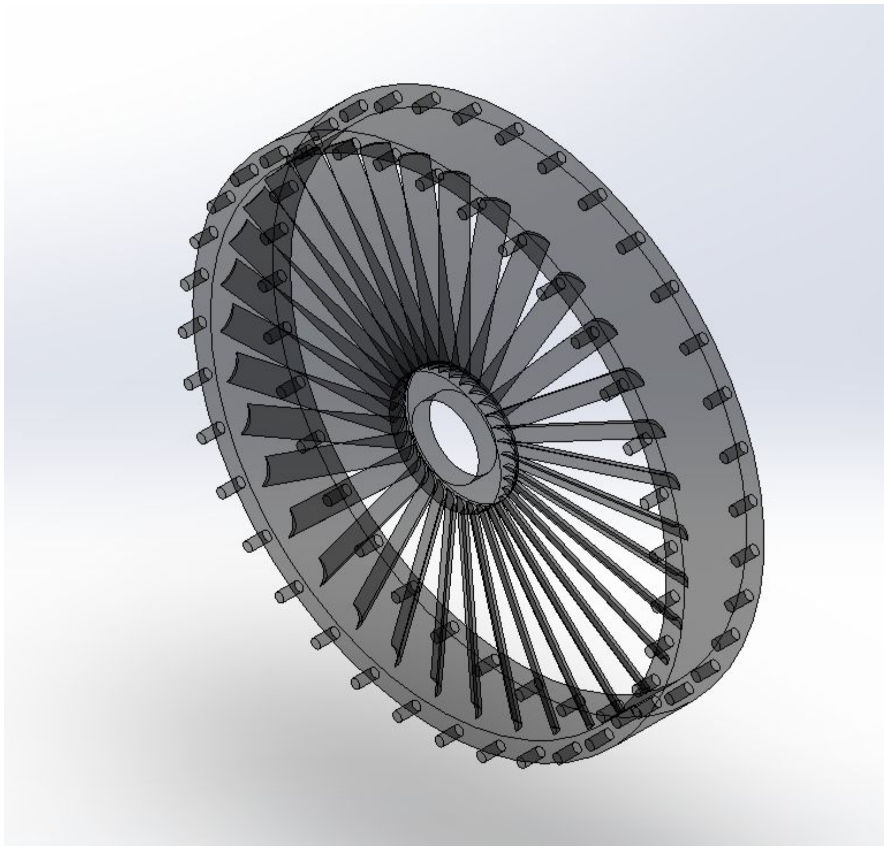


Figure 22: Stator Structure

5.1.5 Shaft

The shaft will purchased off the shelf as a ¾" aluminum keyed shaft. The purpose of the key is to lock the turbine and compressor staging in locations. The rotating shaft should have as little friction as possible in order to generate the most electrical work from the rotation. Having the internal energy of the flow captured through the turbine section via kinetic energy will increase the rotation of the shaft. By maximizing the rotation of the shaft, the brushless DC motor will be able to generate more power.

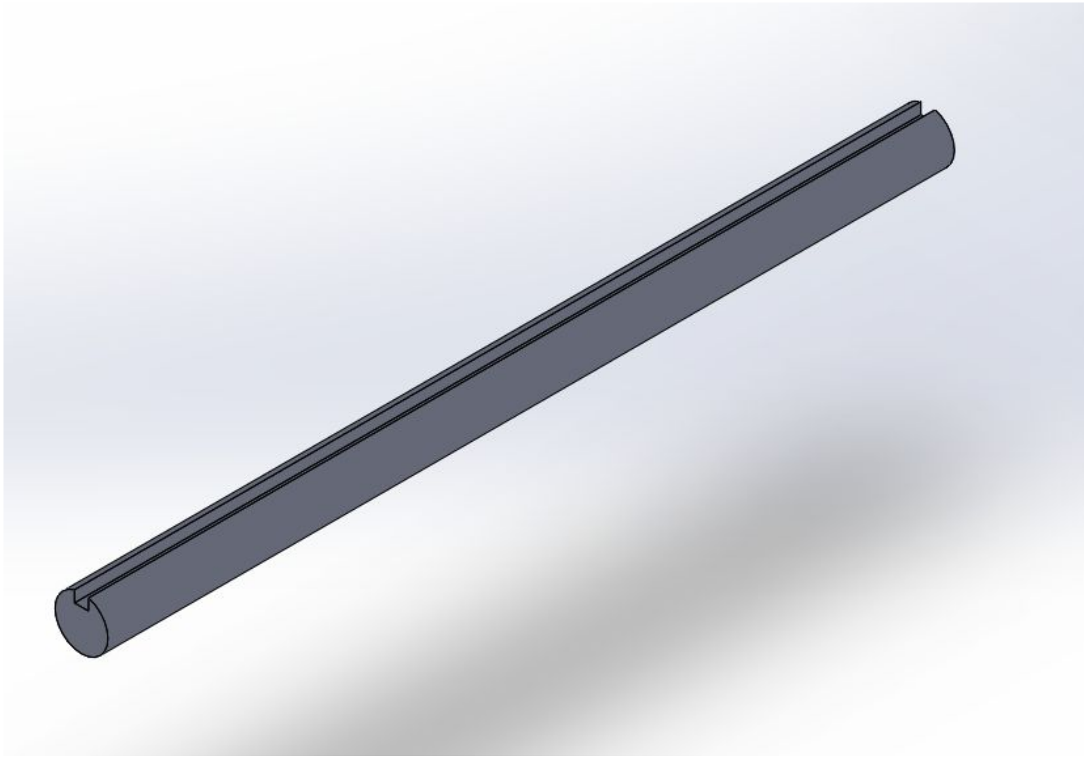


Figure 23: Keyed Shaft

6.0 Proposed Design

The proposed design incorporates the locking mechanism of the casing in order to allow for quick assembly and disassembly for educational purposes. With extending the shaft out of the entire casing, it will be possible to attach a brushless DC motor to generate power from the rotating shaft. The power generated will be connected to a LED lightstrip to demonstrate the capacity and capabilities of the operational Brayton Cycle. Below are CAD models of the current design of the project. The yellow section is the compressor and the blue section is the turbine with the heating chamber located in between the two sections. Multiple items are not pictured in the CAD model, however they are still important to the function of the cycle. What is not pictured is the air compressor to blow air into the system, the dc generator, and the LED light strip. Similarly, the pressure transducers and thermocouple will be implemented to capture real time data for students to see.

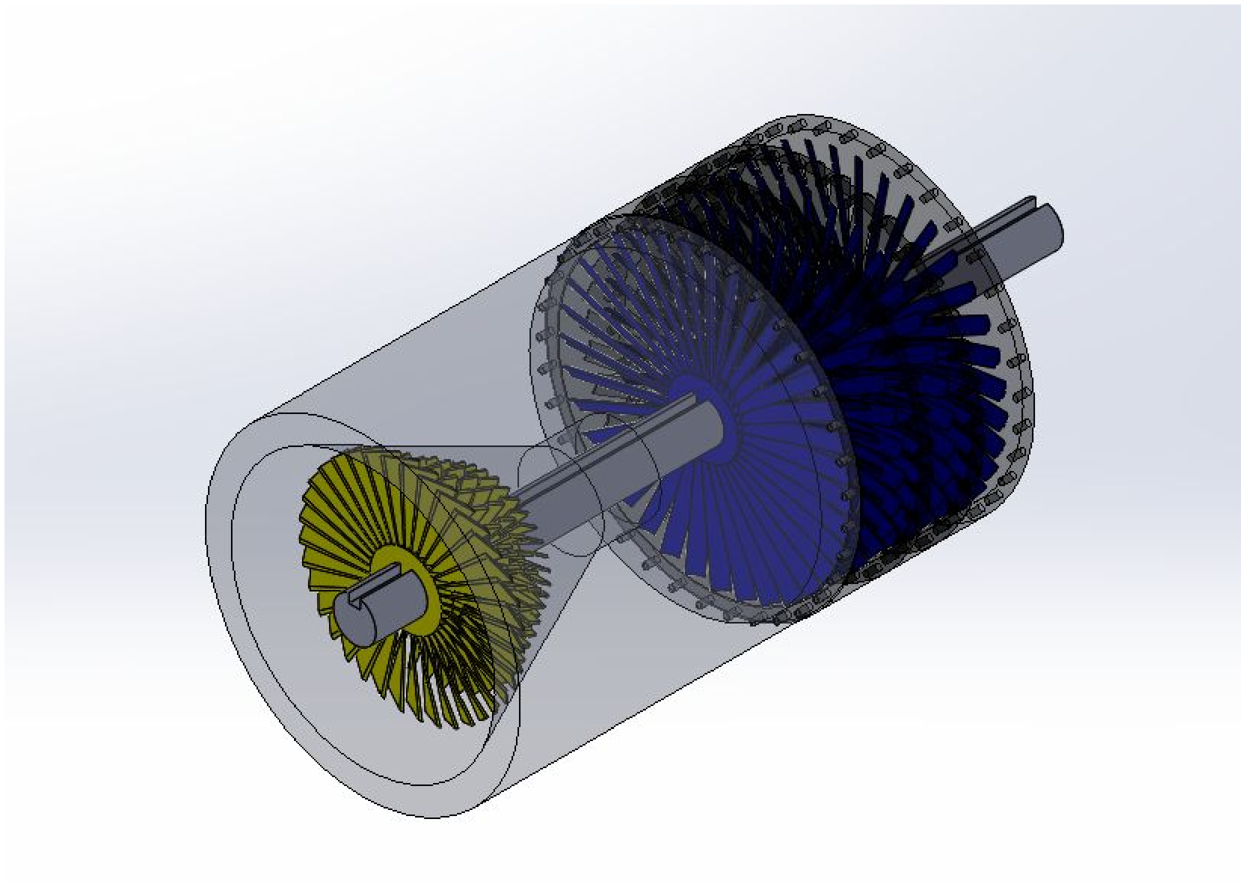


Figure 24: Entire Assembly, Spring Design

Figure 24 shows the direction of the project design. Design has been altered to further break the casing section at the end of the compressor region to allow quick access. Figure 25 shows the updated schematic for the new design iterations.

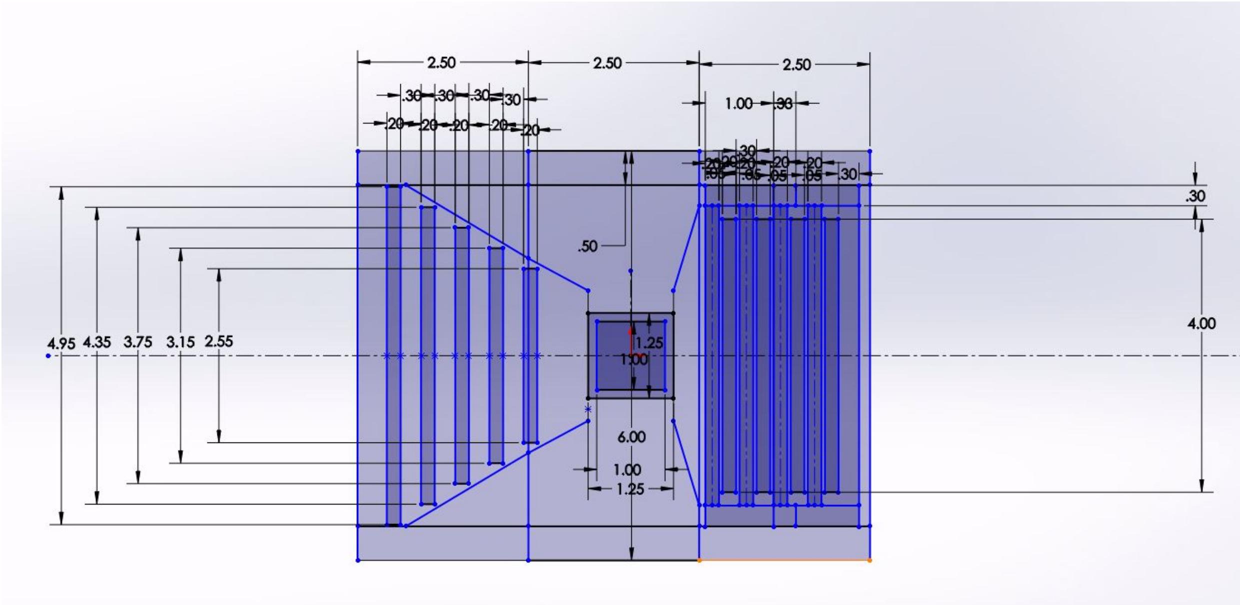


Figure 25: Schematic for Placement

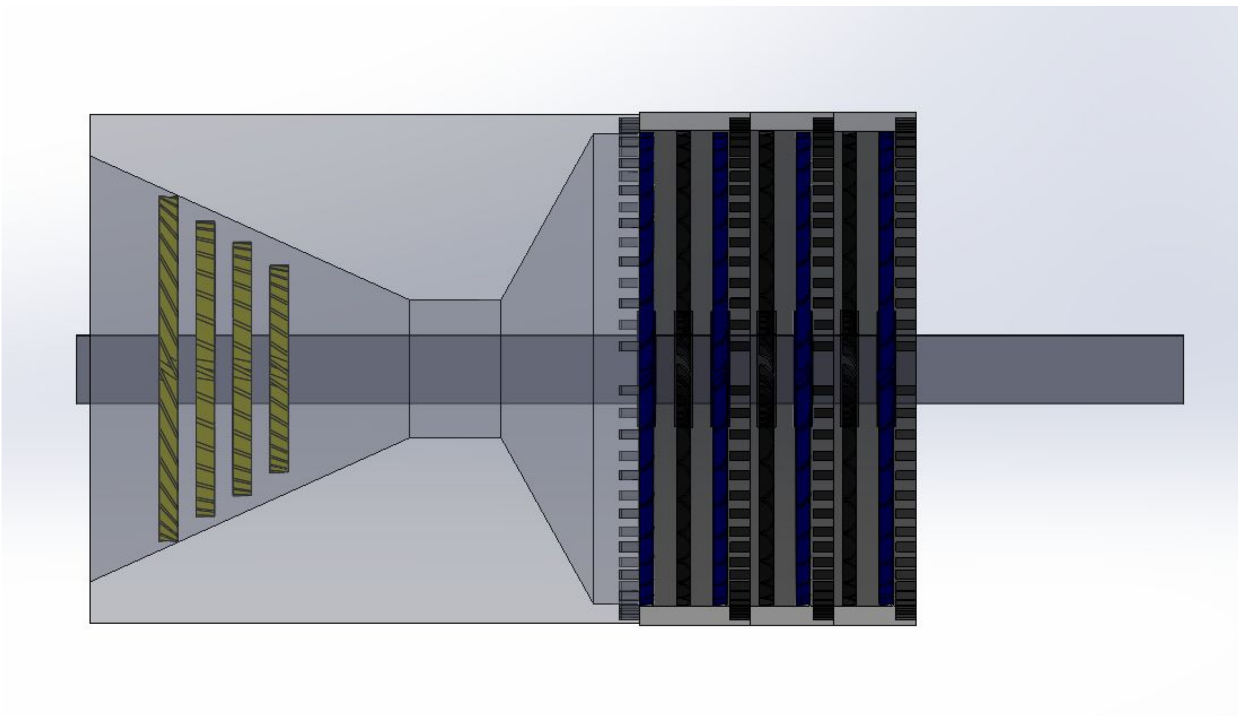


Figure 26: Side View of Brayton Cycle

7.0 Bill of Materials

We looked to these materials and we have to purchase them in the coming days. A list of the materials needed with cost per unit and amount needed. These items are found online or in store. The estimated total, without the cost of printing and testing designs is $350. Table 7 below shows the current budget of the project.

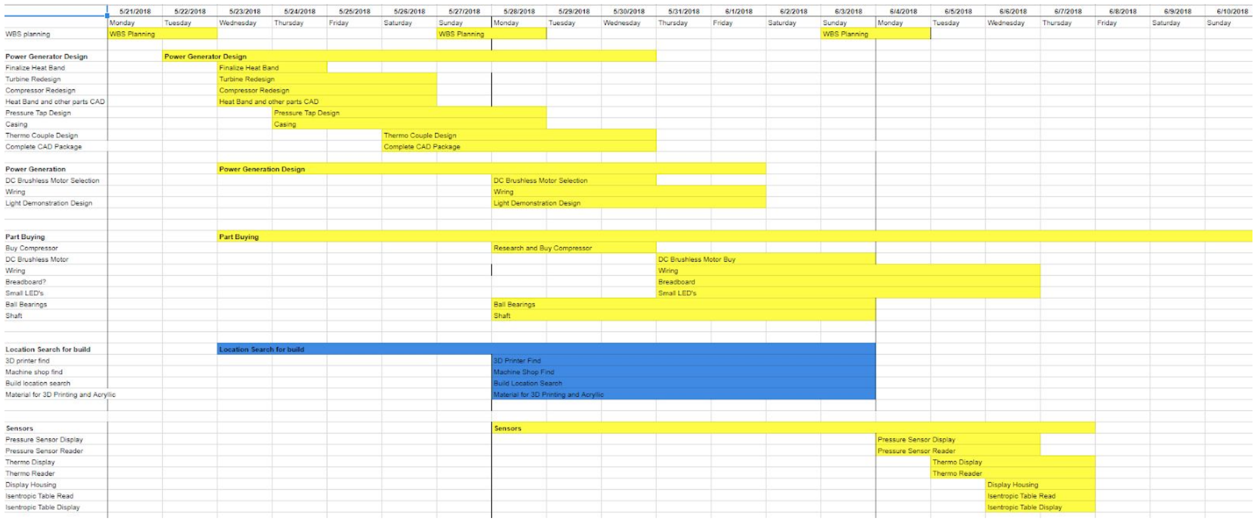
Table 7: Proposed Budget

	Material	Cost per Unit	Estimated Amount	Manufacturer/Vendor	Part Number	Total $
4.4W per ft	LED Light Strip	$7.50	1	SolidApollo.com	SA-LS-RGB-5050-180-24V-1F	$ 7.50
	LED Wiring	$1	2	Superbrightleds.com	24AWG	$ 2.00
120V	Air Compressor w/ 2 Gal Tank	$80	1	Pulsar/Aircompressorsdirect.com	B01E17KX8G	$ 80.00
	Pressure Regulator	$15	1	Apollo/Home Depot	THDCOM103	$ 15.00
up to 15 W	DC Generator	$20	1	Pacific Sky Power/Amazon.com	B01KMZQT1Q	$ 20.00
100 W	Band Heater	$28.50	1	TEMPCO/grainger.com	NHL00100	$ 28.50
	Tubing and Connections	$20	1	Home Depot	530048	$ 20.00
	3/4" Aluminum Shaft	$48	1	McMaster-Carr.com	1570K63	$ 47.50
	J Type Thermocouples	$4	6	NAU	1980-024	Provided
	Pressure Gauges	$7.50	2	PneumaticPlus.com	PSB15-160	$ 15.00
	Pressure Transducer	$49.00	2	Trandocers Direct	TDH30BG025003B004	$ 98.00
	Bearings	$4	5	VXB/VXB.com	608ZZ VXB	$ 20.00
					Estimated Total:	$ 353.50

8.0 Schedule

Scheduling has been generated to guarantee project completion. Table 7 shows the proposed plan for the summer semester that has been adhered to.

Table 7: Proposed Plan for Summer Semester



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Appendix

Equations used for compressor section:

$\tan^{-1}(1/\phi) = \alpha$
$\omega = V_t/r$
$V = V*\cos(\theta)$
$Re= \phi *V*L\vartheta$
$Q = A_i * V$
Mass flow rate = $\phi * Q$