Thermodynamics Demonstration Unit 1B
Power Generating Turbojet Engine

Midpoint Report

EGR 486C-01

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1. Background

The purpose of this report is to demonstrate the midpoint progress of the team, and the plans for the remainder of the semester. Progress for the project has reached 77% completion, the remaining percentage is discussed in the Implementation section of the report. Starting the production of an operating power generating Brayton Cycle required research from Northern Arizona University staff and research from textbooks.

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. Requirements

Research performed required meetings with NAU staff to outline customer requirements and the engineering requirements associated with them. All requirements were assembled in a house of quality which provided insight into the most critical components of the project. Following research for requirements, the team outlined testing procedures for the quality check of the built 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 Procedures

Testing procedures were generated for each main component, each procedure is related to the projects engineering and customer requirements while maintaining paramount safety. The purpose of the testing procedures is for two reasons, a quality check of the project and a operating manual for safe and reliable usage. Each component has been analyzed to create a specific quality check and operation.

Quality Check

Power Test
Tools: Multimeter
Procedure:

Measure motor resistance for quality assurance
Measure voltage and current generated from motor

Heat Test
Tools: Thermocouple
Multimeter
Procedure: Check heating element temperature is below 240° F
Check thermal fuse is operational with multimeter
Check Aluminum Shroud is safe to touch with thermocouple

Pressure Test
Tools: Multimeter
Computer
Procedure:
Measure Voltage generated from pressure transducer
Check all wires are connected and communicating to computer

Speed Test
Tools: Stroboscope
Procedure:
Measure rotational speed of shaft
RPM not exceeding 1500 for safe operation

Operating Procedure

Ignition Procedures
Plug in main power cable
Begin Air Compressor to 60 psi
Release Valve to Turbine Section
Turn Valve to Compressor Diffuser

Heating Element Operation
After Ignition is completed and running
Turn on heating system
Safe Run Time: 20 minute, continuous

Temperature Acquisition Operation
After LED system is continuously operating
Plug in Temperature position one
Acquire Data
Plug in Temperature position two
Acquire Data

Pressure Acquisition Operation
Plug in Pressure position one
Acquire Data
Plug in Pressure position two
Acquire Data

Shut Off Procedure

Turn off Heating system
Turn off Power System
Allow system to run until no movement
Unplug main power cable

Quality checks and operation procedures are necessary for the safety of the team and student body that will utilize the project. Simple procedures have been generated for each component that ensures all users have a safe and reliable method of operating the power generating brayton cycle.

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. Existing Designs

3.1 Design Research

Research was performed in the previous semester, as well as an individual analysis this semester. Each component has been researched for the fundamentals that allowed the team member to utilize the knowledge and proceed with design and construction.

Power Research

The LED display is consisting of 24 individual 24 Volt LED bulbs at 4.4 Watt per foot. A 4 pin connector is required to attach the brushless DC motor to the LED strip, as shown in Figure 1. Calculations are provided to demonstrate the current required for two segments of LED lighting to be lit.

Considering a 8 inch segment of lighting, the power required is 2.93 watt.

$$P = i \cdot V$$

$$i = \frac{24\ Volt}{2.93\ Watt} = 0.122\ Amps$$

A DC motor has been selected with a resistance of 5 Ohms and a torque constant of 21.1 mNm/A (milli-Newton meters per Amp).

$$V = i \cdot R + K_e \cdot \omega$$

$$\omega = \frac{24\ Volts - (0.122\ Amps)(5\ \Omega)}{21.1\ mNm/A} = 110.85\ rad/s$$

Casing Research

The purpose of designing a casing around a Brayton cycle, specifically at jet engine related cycle, is to channel the working fluid through the system safely. This report will detail the material chosen as well as the rationale behind the design. A past option for a casing design was to form an acrylic tube to the shape the team decided; The design would not be time effective and was too expensive for the project's budget, however. The current design was chosen because of how time and cost effective it is.

The material chosen for the casing is PLA 3D printer filament provided through NAU. PLA filament is a common material because of the applications of the prints. PLA filament does not need special equipment like other filaments would and has low warp qualities after prints. Unfortunately, the 3D printers provided through NAU do not allow teams to purchase specific filaments for use. The color of the team's design was supposed to be clear. However, current clear filaments have a milky white quality that does not allow much transparency. To account for this, the team decided to alter the design to allow visuals to the inside. This is discussed further in later sections.

Blade Research

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 System Level

The purpose of the project is to design and operate a power generating brayton cycle that allows for the education of introductory thermodynamic principles. The operating Brayton cycle is able to educate under three main parameters related to engineering and thermodynamics. A brayton cycle operates by producing power through compression and expansion, thermodynamic work output principles. The principles utilized for work production, is directly related to power energy analysis. The blades designed for the compressor and turbine sections are related to airfoil analysis relating to the flow of the fluid.

3.3 Subsystem Level

Each system level can be further analyzed that present relevance and applicability to the project and topics related. System levels have been broken down to further elaborate the educational principles related to the project. Thermodynamic principles have been broken down into diagrams, expansion & contraction, and heat input. Power generation has been segmented into a turbomachinery analysis, DC motor analysis, and power efficiency analysis. Airfoil analysis has been broken down into turbine analysis, compressor analysis, and flow analysis.

Thermodynamic Work Output Principles

T-s & P-v Diagrams:
Performing a Brayton Cycle analysis with irreversibilities is directly related to the project assembly. Assuming that the turbine and compressor efficiency is at 90% and a compression ratio of two, a work output is .46 kW. Figures X and X are the calculations performed for the current system parameters, as well as displaying thermodynamic educational principles.

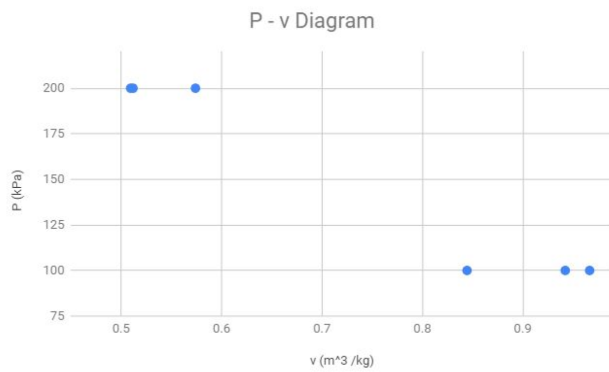

Figure 1: P-v Diagram

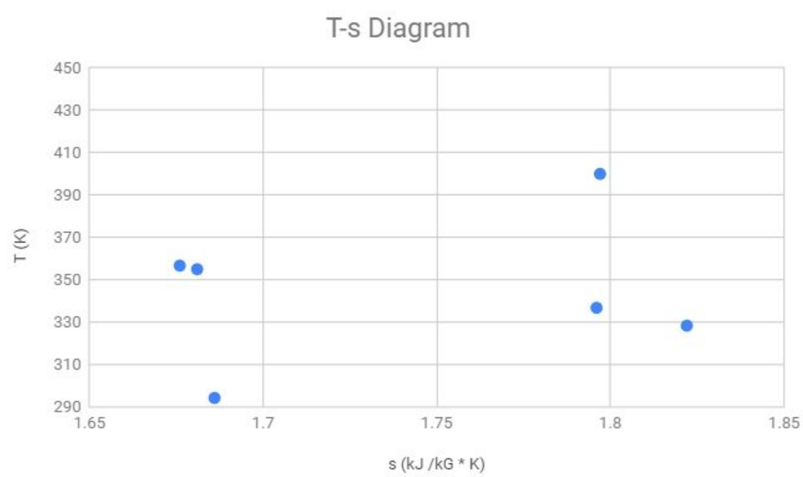

Figure 2: T-s Diagram

Expansion and Compression:
Compression in thermodynamic principles increases the temperature of the system, the purpose of this analysis is to demonstrate the efficiency of the compressor section.

Calculating the pressure before and after the compressor section allows for the compression ratio necessary for the work output equations.

Heat Input:
Inputting heat into the system increases the energy of the system. The purpose of this analysis is to allow for the calculation of efficiency of the heater, as well as the efficiency of the entire system. The more heat put into the system, the better the cycle will operate.

Power Generation

Turbomachinery Analysis:
Utilizing the turbomachinery equations, it is possible to calculate the work output due to the decrease in rotation of the shaft. Although turbomachinery analysis does not occur in a elementary thermodynamic class, it is useful for Fluid dynamic analysis.

DC Motor Analysis:
To calculate the amount of power the DC motor can produce it is necessary to measure parameters of the system. Measuring the resistance of the motor and the torque characteristics leads to the induced voltage generated from the rotating shaft. By performing a DC motor analysis, fundamentals of electrical engineering are tested.

Power Analysis (Difference of input vs. output):
Following thermodynamic educational principles, a component efficiency analysis must be performed. Calculating the efficiency of the compressor and turbine sections will dictate the performance of the cycle and the amount of power generated. Problems from thermodynamic textbooks about Brayton Cycles with irreversibilities can be illustrated by performing a power analysis of the cycle.

Airfoil Analysis

Turbine Analysis:
Similar to calculating the efficiency of the cycle, it is imperative to measure the efficiency of the turbine stage. By minimizing irreversibilities, it is possible for future classes to inspect the project and analyze how to improve turbine blade design along with turbine efficiencies.

Compressor Analysis:
Compressor blade design is meant to compress the moving fluid into a higher state of energy before the input of heat. By analyzing the blades selected from the flow regiment, design and compression ratios can be calculated.

Flow Analysis:
Although not directly related to introductory thermodynamic classes, flow analysis is crucial for all engineering students. Flow analysis is the flow regime of the working fluid, i.e the reynolds number and turbulence of the fluid.

4. Designs Considered

Casing Reduction Alternative:

Prior to the design selected in the CAD model, the team considered a visible alternative to the casing. The purchase of a dog cone, allowed all blades to be seen while moving. A reason for the dog cone not being selected was the increase of space between blades and the casing which would greatly reduce performance.

Two Stage Ignition:

Due to the large diameter of the keyed shaft, the team has worked on a two stage ignition for the introduction of air into the Brayton Cycle. By directing the air into the turbine section, which blades are designed for the grabbing of air, the shaft can get a jump start for ignition. Once the shaft has begun rotation, the valve would be switched to allow air to only be introduced in the compressor region. This idea is still being worked out as the design process of the ignition stage has yet to be completed.

Analog Pressure and Temperature Systems:

To meet the demands of the client, the team has focused on a digital system to acquire data from the working Brayton Cycle. The original idea of the team was to have manometers and temperature gauges on a wooden board behind the system that would physically illustrate the pressure and temperature states. This idea would allow the entire project to be mobilized quickly without the need to set up a computer to run the data process.

Voltage and Current Output Sensors:

Similar to the analog temperature and pressure readings, a voltage and current meter would be mounted at the end of the model. By presenting a analog system of reading, the project would allow quick and immediate power readings. This idea has not been finalized out of the project, it is determinate on the completion of the power output system.

5. Design Selected

5.1 Rationale for Design Selection

Heating System

In Brayton cycle, working gas is heated at constant pressure. In most of the application involving Bryton cycle involves heating of working fluid to obtain higher work efficiency with system [1]. In our model setup, we also need to provide a heating system as Bryton cycle requires heating of gas in its cycle. Conventional method used was to burn the fuel and provide heat to gas for heating but in this model, because of compaction and safety purposes an electrical based heating system is designed and fabricated. Fuel burning would have required a separate fuel supply, which can provide continuous fuel, an air inlet to provide oxygen for exothermic reaction, and as a result, design would be complicated because we have to provide a constant pressure environment for Bryton cycle. Connections and components to provide such setup would have been costly as well as risky to operate for demonstration purposes of a compact model. Also for our setup, we do not require to provide very high power values at high efficiency so we can work with relatively lower temperature that can be obtained by small setups based on resistive heating.

Heat Calculation

Factor of safety is the ratio between the maximum value at which a component can be functional by the max operational value in design for that particular component. Factor of safety is define for each component and criticality of the system is taken care off to provide safe operational model. That is the reason that heating band safety factor is much higher then the remaining components because it is the most critical component in heating system. Further system is make safer by providing heating insulation as well electrical insulation by end capping all electrical connections joint.

Calculation for heat band can be performed by considering the operational value requires to fulfill the model requirement. Total heat requirement for our model can be divided into two parts namely [2]:

1) Heat required for start-up
2) Heat require for continuous operation

Both of them are being calculate by using following correlation:

Start-up watts = Power required in given time to reach operating temperature + load material heat absorption + safety factor

Similarly, the heat required to sustain the operating temperature can be calculated as follows:

Operating watts = Power required to maintain the operating temperature + load material heat absorption + safety factor

It is important to note that the wall losses are neglected in these calculations. Moreover, ultimate results obtained are shown in table 4 below.

Band Heater

Heating system was to be designed as per the required temperature at the inlet of turbine. In order to produce 20 Watts at the inlet we do have to consider the efficiency of turbine. As our customer needs 20 Watts production power from turbine so if we assume a turbine with efficiency of 70 then,

$$\eta = Pout/Pin$$

$$Pin\_Req = 20/70*100 = 28.5 \text{ Watts}$$

As per the model designed, calculations were performed to calculate the heat required for system. It was calculated that heating system was to heat the air for turbine inlet and

100 °F was to be achieved for turbine inlet in model. Let's us ignore the losses in Bryton cycle and assume for simplification that no loss takes place then in ideal Brayton cycle the max power that can be produced is given by [3]:

$$P = \dot{m} \times c_p \times T_a \times [\frac{T_c}{T_a} - 2\sqrt{\frac{T_c}{T_a}} + 1]$$

P= Power

$\dot{m}$ = Mass flow rate

C_p = Specific heat of air at constant pressure

T_a = Atmospheric Pressure

We need to obtain T_c which is turbine inlet temperature = 100 °F, which can be obtained by manipulating heating system. So now by considering ideal situation of no losses from Bryton cycle to air entering turbine from inlet, we obtain that 100 °F temperature is required to get required output power.

Table 4: Thermodynamic parameters and their values

Sr. No.	Quantity	Value
1	Output Energy from Turbine	~20
2	Inlet Temperature Required	100 °F
3	Mass Flow Rate	0.00004 slug/sec
4	Atmospheric Temperature	75 °F

Heating system is designed by considering compact and economical safe setup that can fulfill the minimum requirements of heating system. The amount of heat absorbed for required temperature consists of two parts. Heat required for start-up and heat required to maintain the desired temperature of 100 °F as mentioned in heat systems calculation.

Heating band was to be installed at the center of chamber therefore a compact design was required. A CAD design was made as shown in fig 1 to be installed for obtaining required temperature of working fluid to have more work output in our model setup. Based on that requirement, Tempco® band heater of 150 watt with max temperature capacity of 900 °F is used for heating purpose. It can easily increase the temperature of air from room temp to 100 °F. It was selected because of its lower cost at high watt density of 40 Watts/In^2. It has mica insulated steel inside and corrosion resistant Stainless steel grade outside to **increase its life** and protect it from rusting. Factor of safety for this instrument is taken as 6 i.e. (900/150) because of its criticality

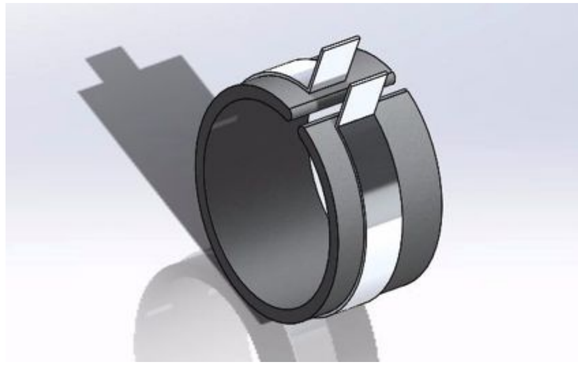

Figure 3: CAD design of heating band

Figure 4: Heating Band

Figure 5: Thermal Switch

Temperature Control

In heating system, heating is required to be controlled as it can reach to max value of 900 °F which is disastrous for model. Safety of the band heater is required to assure for safe function on model in long term. It is required to connect it with a thermal fuse in order to run the model safely and if the temperature goes higher, it will disconnect the connections to turn the heating off to avoid any problem.
A snap disc control is selected for that purpose. Snap disc control is used which has the feature of adjustable limit ranging from 170 to 250 °F. It has automatic reset option in it that helps in increasing the life of model. It was installed in series with band heater. Assembly was put into the casing and fastened to avoid any vibration or damage due to their movement. Since our required temperature value is below 170 °F so upon crossing the required value, heating will be stopped to avoid any damage of equipment. It has automatic reset option in it and can be again turned on. Since this component is regulating the heating system, the safety factor for it is important to consider and it comes out to be 2.5 for our thermal switch.
For a continuous heat flow, as per the thermodynamic law, a heat sink is also required with heat source in the system. By completing circuit, continuous supply of heat to rise the air temperature of 100 °F can be achieved and maintained for longer time.
Heating chamber is since providing mechanical support as well for the model so heat sink is designed and selected made up of steel. A Computer Aided Design drawing was initially made for system, shown in fig 6 and later sink component made of steel is used in model as shown in fig 7.

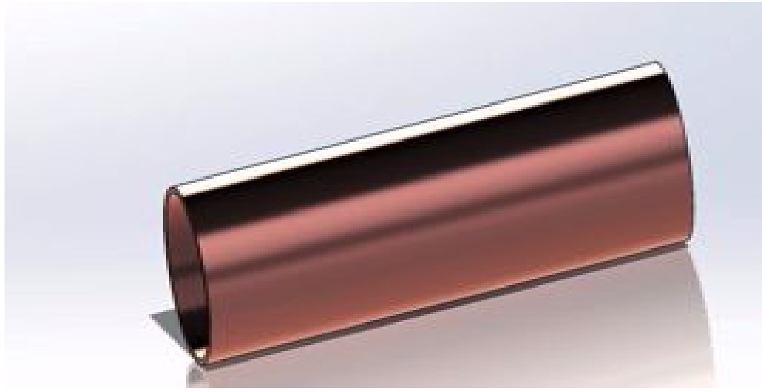

Figure 6: Heat Sink CAD Design

Figure 7: Heat Sink

Temperature Measurement

Temperature is to be measured for record and generate T-S diagram on output. Required temperature measurement is performed with j-type thermocouple. J-type thermocouple are selected based on its greater accuracy in lower cost in our interested temperature ranges. In order to maintain the compaction, thermocouple legs are inserted in the casing while output reading are viewed outside of the casing. By change in composition at thermocouple legs, a voltage will be generated. Difference in generated voltage will exist at same temperature due to two different materials composition, which is then translated back to temperature as per calibration [4].
Preferably the required data for Brayton cycle, pressure and temperature readings are taken at similar points. Therefore, along with pressure gauges, J-type thermocouples were installed in the same drilled hole as it for pressure sensors. By choosing same drilled holes as of pressure sensor enables to plot P-V and T-S diagram at same reference points. Ultimately, real time data was obtained and stored with LabVIEW for record and generation of T-S diagram.

Figure 8: J-Type Thermocouple

Installation and Testing

Before installing heating system into the model, it needed to be tested for fulfilling the requirements in safe way. For that, heating band was operated with thermal switch in series connection to provide safe operations. J-type thermocouple was also attached to directly read the temperature of system. Electrical power was provided and the system was placed on concrete surface along the wall to test it operational characteristics. The system along with its complete connections is shown below in figure 7.

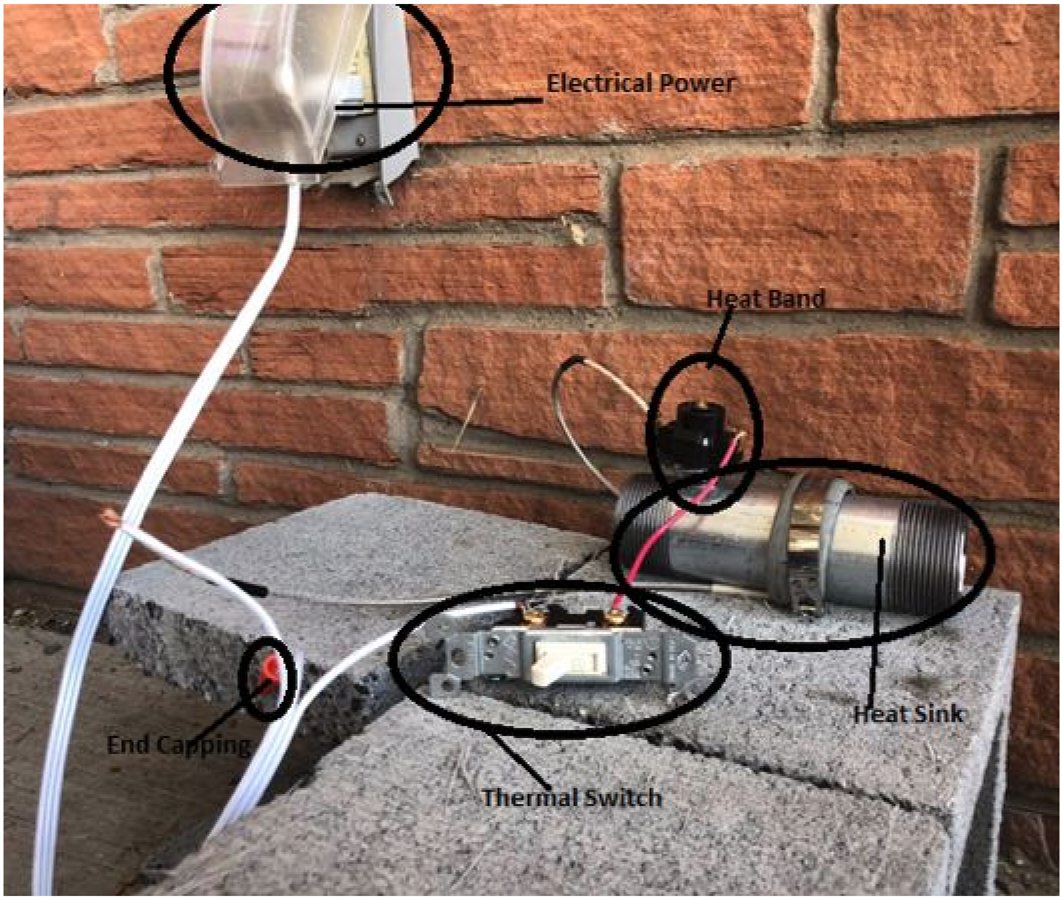

Figure 9: Heating System (Components and Connections)

Power was turned on and current starts flowing through the circuit. Temperature starts rising due to electrical resistive heating in band heater. After short interval of time, heating was observed in system. System was made to run for 18 minutes as per requirement of design that have to be run for at least 15 minutes. Once the system remained functional, the system was then turned off. Slight burning was observed on surface as it can be seen in figure 8 below.

Figure 10: Burned Concrete Surface

The burned surface shows that system is operational and working as per requirement. For temperature verification J-type thermocouples are designed to attach through casing that can read direct temperature at inlet and outlet of turbine. This system is needed to heat the inlet air up to 100 ^{o}F as per discussed calculation in above heat calculation section. It is quite evident from test run that our heating system can provide sufficient heating as per models requirement.

Safety Measures

Safety precautions are important to be considered for this lab scale class model. It is required to operate for at least 15 minutes in safe was to demonstrate the Bryton cycle for students understanding. Two aspects are to be considered with safety prospect in heating system here in our model. Electrical safety and heat safety are the major safety concerns in our system. Electrical connections were made between heating band and thermal switch. Power was being provided from main electrical connection of 110V. Therefore in order to make it safer, end capping was done to electrical connections for isolating purposes. It is shown in figure 9 below.

Figure 11: Electrical Insulation by End Capping

Thermal insulation was also required to make heating system operation more safer. In result of thermal safety measure, the system would not be damaging in any scenario during experiment running with model, which is one of the basic requirement for this model. Therefore, an aluminum casing was bought for this purpose which will contain this whole setup in it to avoid its contact with casing and other instruments in the model. Aluminum casing was economical as well as can serve our purpose. The casing to be used is shown in figure 10 below.

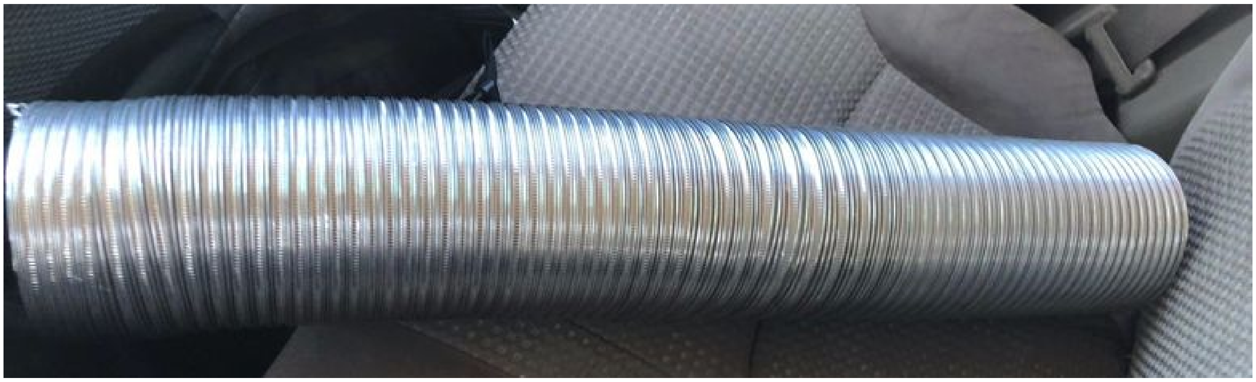

Figure 12: Aluminum Casing for Thermal Safety

Results and Discussion

A compact educational model for demonstration of Bryton cycle is designed and fabricated. Components of the model were designed as per the customer requirement and were assembled by taking care of its proper functioning and reliable operation for long time. Qualitative and quantitative analysis were performed to obtain parametric value and rated components against those requirements. Safety with economical design was considered and fabricated. Components of heating system was selected on basis that they produce heat required at the inlet of turbine to produce required output power and provide long time safer operations. A heating band with a temperature controller was designed and brought to install in Bryton cycle model. In order to have better efficiency a heat sink was provided as per design requirements to reach a higher efficiency of heating system. Temperature was controlled with a temperature controller in the safe range of temperature. Temperature were recorded at each critical point including inlet and outlets of turbine, heat exchanger and bypass area. This data is then ultimately used to draw T-S diagram to be used in Bryton cycle. End capping of the electrical connections was performed to provide electrical insulation. An aluminum casing to contain the heating system was used to provide thermal safety as well. Reliability and safety factor were considered in all components to provide a durable safe and compact system. Economics and performance is optimized in design with safe operations. It can be said that this resulting low cost model is excellent for demonstration purpose of Bryton cycle to students to develop deep understanding.

5.2 Design Description

In this section, a complete and current CAD model is presented with images of the first and last blade of each section. Presenting the first and last blade of the sections allow for the quick visual of how the blades change over the extent of the keyed shaft. A heating band schematic has been produced to illustrate the work done for the operational heat band.

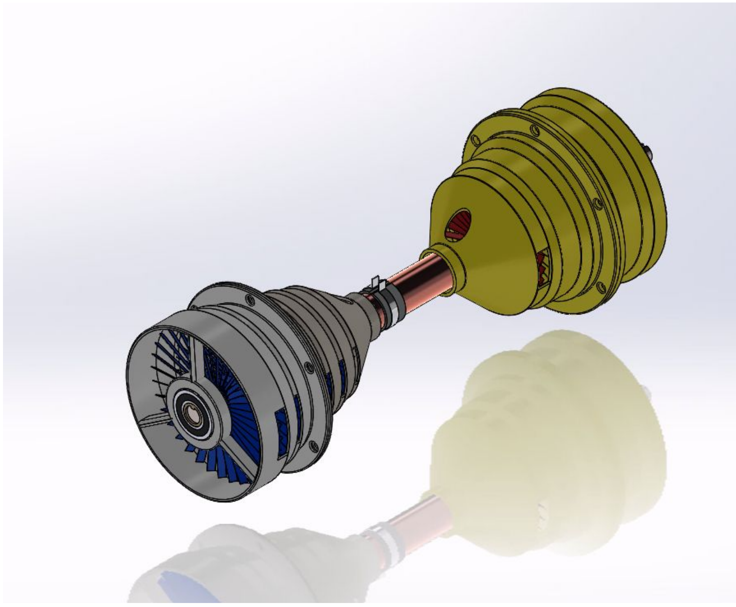

Figure 13: Assembled CAD Model

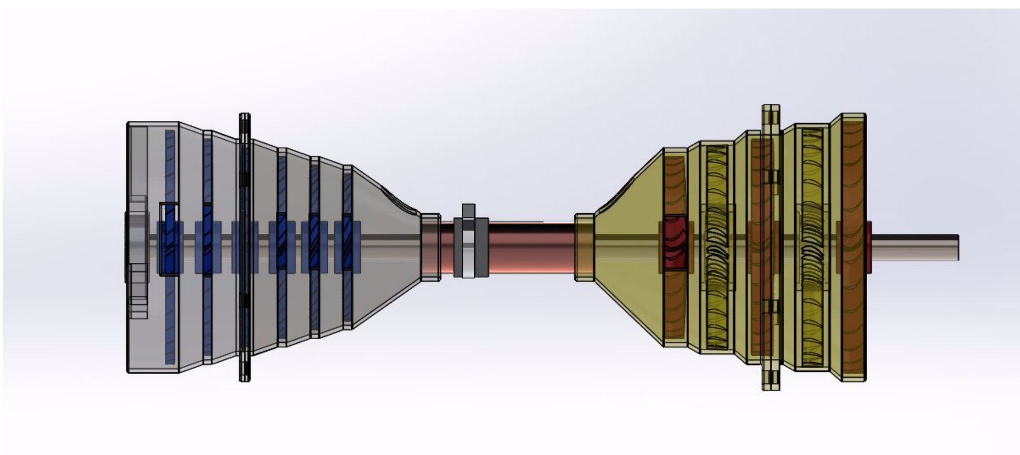

Figure 14: Side View CAD

Figure 15: Exploded CAD Model

Compressor Section

To minimize irreversibilities in the compressor section, each blade distance has been measured to allow for a tight fitting compressor casing. The casing has been sliced in half to allow for 3D printers to print the whole assembly. Connecting the two halves requires a series of six bolts. On the sides of the casing, slots have been cut out to allow students to see the inner workings of the compressor. To allow visuals and minimize air pressure, acrylic paneling will be utilized to seal the viewing slots. Circular cutouts near the heating band connection are necessary for the pressure transducer to operate.

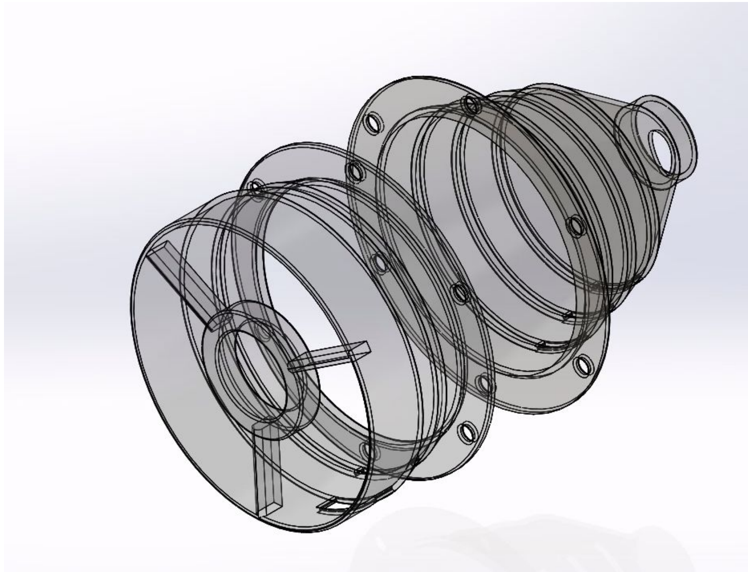

Figure 16: Compressor Casing

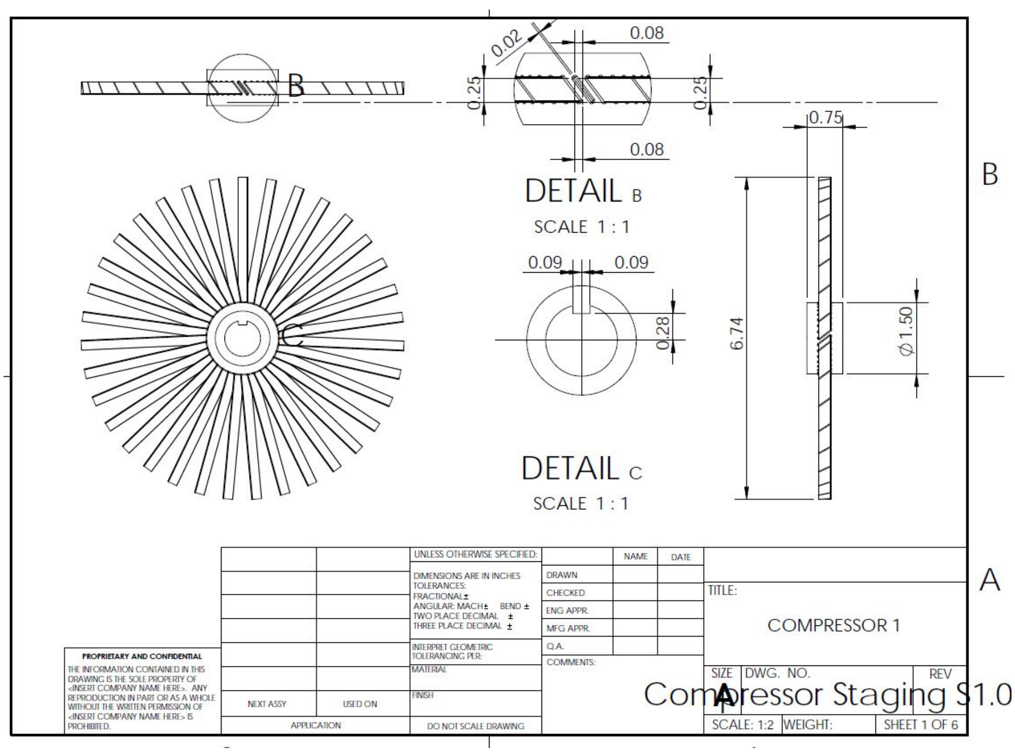

Figure 17: Compressor 1 Dimensions

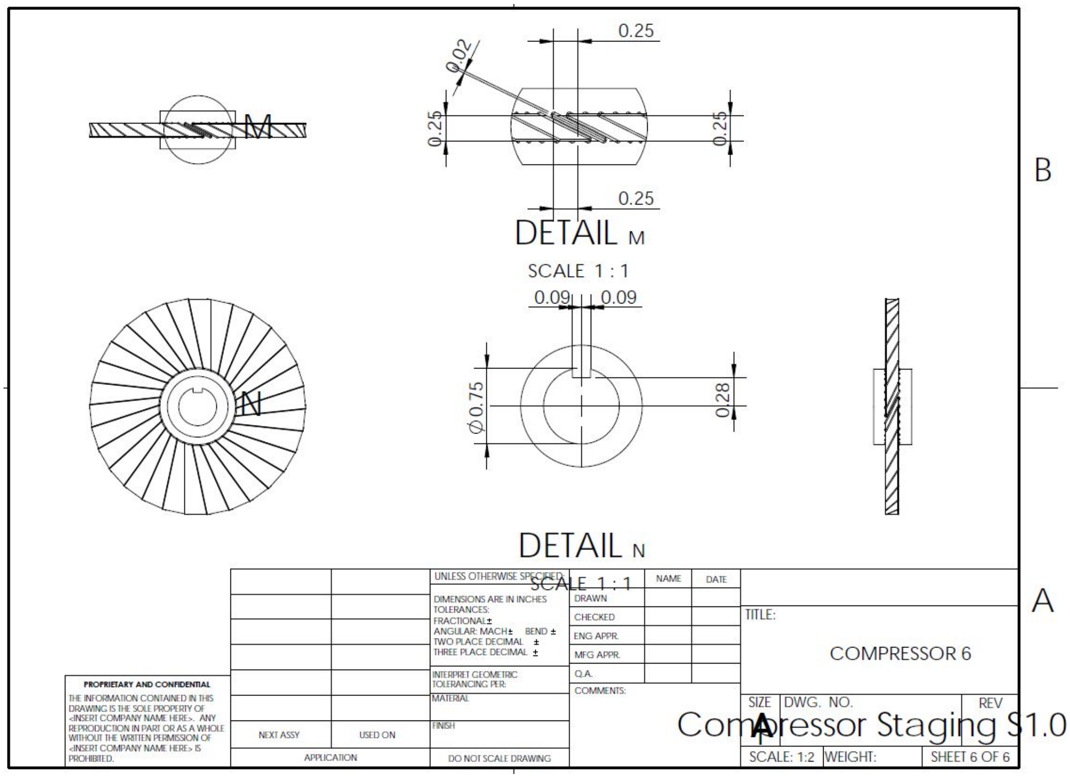

Figure 18: Compressor 6 Dimensions

Turbine Section

Similar to the compressor casing, the turbine casing has been split in half to allow printing of the assembly. The turbine section contains two stator stages in the casing, which is necessary for the redirection of airflow for the turbines, and structural support for the entire assembly.

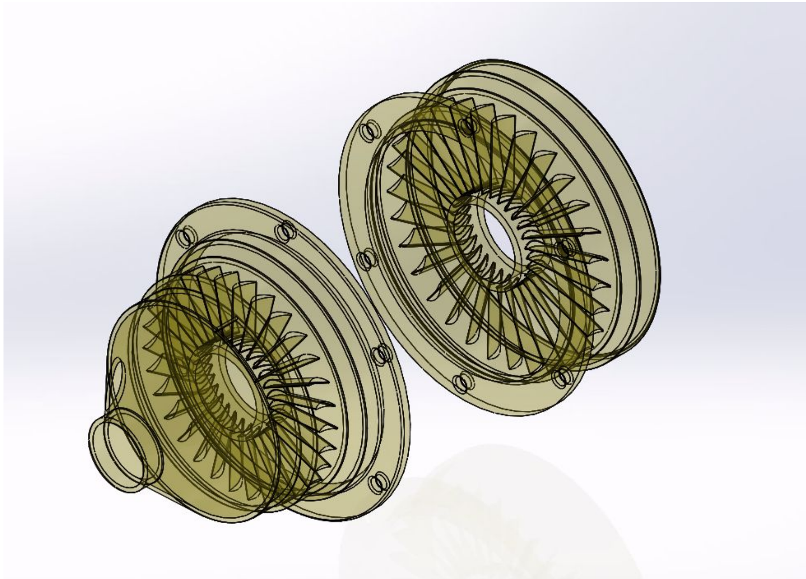

Figure 19: Turbine Casing

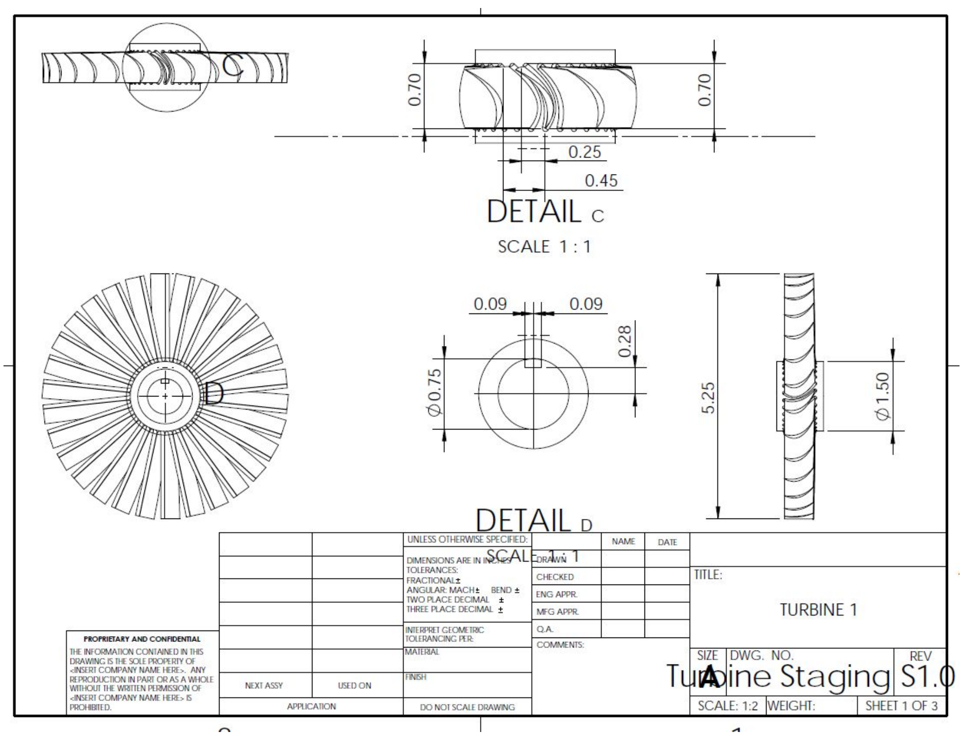

Figure 20: Turbine 1 Dimensions

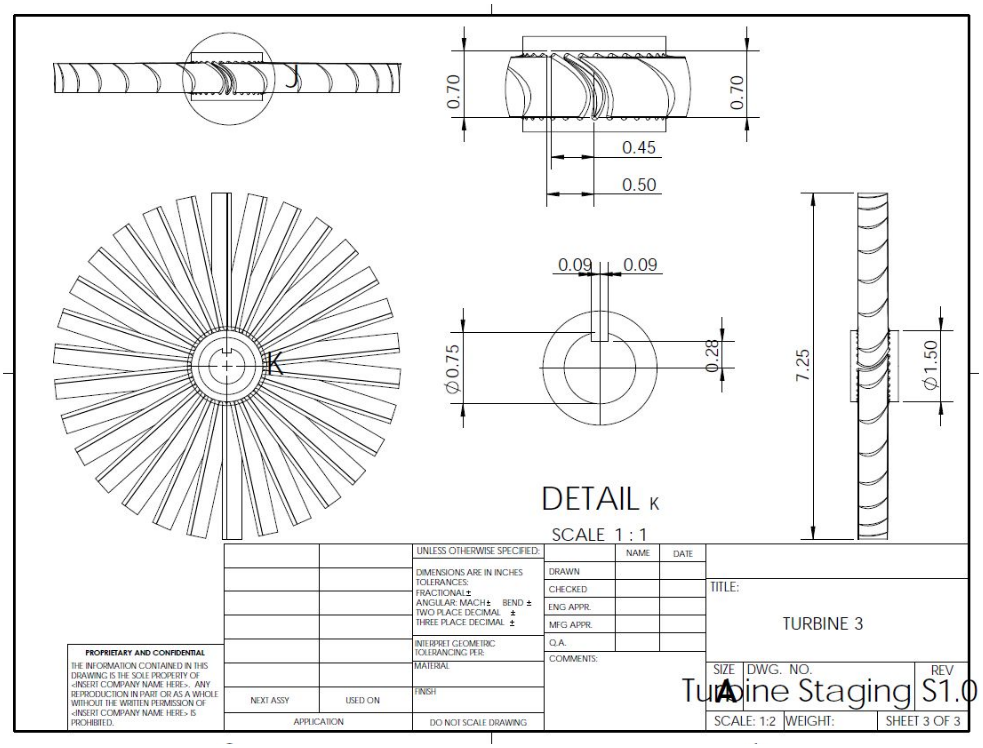

Figure 21: Turbine 3 Dimensions

Heating Section

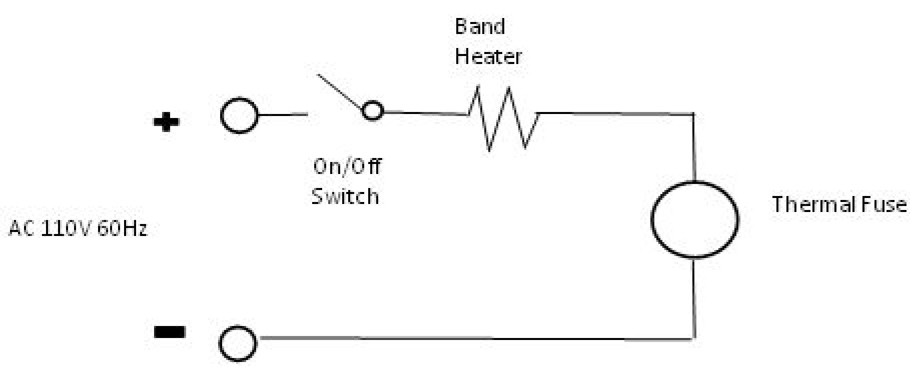

Figure 22: Heating Element Schematic

6. Proposed Design

Designing and constructing a power generating cycle has required alternative designs, as illustrated in Section 4 Designs Considered. The current system is proposed in Figure X, while the continuation of CAD drawings have been provided in previous section. In this section, the proposed design in the previous section is further elaborated with the planning management for the remainder of the summer semester. A working Bill of Materials is in the appendix section of the report and consists of the purchased items.

Table X is the current progress of the team. The table has been broken down to demonstrate the work produced since the start of the summer semester, the current tasks being worked on, and the upcoming tasks. Table X, is the work breakdown structure which illustrates the time frame for each task completion.

Table 5: Task Management (77%)

Tasks for Team Members	Task Completed	Tasks in Progress	Tasks to Complete
3D Print (Erich)	Ball Bearing Casing Designed CAD CAD update Keyed Shaft purchased Blade Staging Printed (9)	Printing Bearing Casing Printing Turbine Casing Printing Compressor Casing	Updates (Pending)
Casing (Gavin)	Case Shape designed Material Selected	Purchasing Bolts Plywood Construction Purchasing Cart	Assemble Casing System
Heating System (Hamad)	Heat Band purchased Thermal Fuse Purchased Heat band power input built Power Switch assembled	Assemble safe housing and wiring	Thermal Insulation Wire Management with cart
Pressure System (Abdullah)	Pressure Transducer purchased	p-V & T-s diagram for power output ranging from 50 - 100 Watt	UI Selection for display and operation
		Purchase Wire for pressure systems	Labview Acquisition
Work Output System (Erich)	LED strip purchased Brushless Motor Selected Motor hub designed and currently printing	Purchase RGB Wiring Assemble Wiring system	LED Display Housing Power Check System
Ignition System (Gavin)	Air Compressor acquired	Purchasing Tubing Purchasing Valve Designing Air Diffuser	Implementation of air compressor to model

Table 6: Current Budget

Material	Cost per Unit	Estimated Amount	Manufacturer/Vendor	Part Number	Cost Before Tax	Actual cost w/ tax	Purchased
LED Light Strip	$14.00	1	SolidApollo.com	SA-LS-RGB-5050-180-24V-1F	$14.00	$15.00	Yes
Wiring	$1	12	Superbrightleds.com	24AWG	$12.00		No
Air Compressor w/ 6 Gal Tank	$89	1	CPOoutlets.com	PCBRC2002R	$89.00		Yes
PVC Pressure Regulator	$5	2	Apollo/Home Depot	THDCOM103	$10.00		No
DC Generator	$20	1	Pacific Sky Power/Amazon.com	B01KMZQT1Q	$20.00		yes
1.5" Band Heater	$32.30	1	TEMPCO/grainger.com	2VXZ6	$32.30	$45.09	Yes
Tubing and Connections	$20	1	Home Depot	530048	$20.00		No
3/4" Aluminum Shaft	$47.50	1	McMaster-Carr.com	1497K31	$47.50	$41.68	Yes
J Type Thermocouples	$4	2	NAU	1980-024	Provided	$0.00	Provided
Pressure Gauges	$7.50	2	PneumaticPlus.com	PSB15-160	$15.00		No
Pressure Transducer	$49.00	2	Tranducers Direct	TDH30BG025003B004	$98.00	$119.98	Yes
Ball Bearings	$4.95	3	HomCo		$14.85	$14.85	yes
3D Prints	$10	12	Rapid Lab/Cline Library		$120.00	$0.00	Continuous
Heat sink	$5.99	1	Home Depot		$5.99	$6.93	yes
Thermal Fuse	$17.60	1	Grainger.com	6UDY6	$17.60		Yes
				Estimated Total:	$516.24	$243.53	

Table 7: Weekly WBS

7. Implementation

To manufacture the designed Brayton Cycle 3D printing, purchasing, and assembly are all required. Implementation of the manufacturing plan required key dimensioning off three critical parts: the keyed shaft, heat band, and radial ball bearings.

7.1 Manufacturing

Manufacturing the designed Brayton Cycle requires printing of the CAD drawings, purchasing of key components, and assembly. This section will provide a list of purchases, a list of 3D printed parts, and components for assembly. Each component has been segmented to display the purchasables, printing, and assembly features.

Table 8: Blade & Cycle Manufacturing

Blade & Cycle		
Print	**Purchase**	**Assemble**
Prototype 1 Stage	Radial Ball Bearing	Casing
Print 9 Stages of Blades	Bolts for Casing	Ball bearing casing for stator
Bearing Casing		
Turbine Casing		
Compressor Casing		

Table 9: Heating Element Manufacturing

Heating Element		
Print	**Purchase**	**Assemble**
	Collar heater	Wiring Schematic for wall
	Thermal Fuse	Safe wiring casing
	Heat Sink	Outer casing insulation
	Light Switch	
	Aluminum Casing	
	Wiring	

Table 10: Pressure System Manufacturing

Pressure System		
Print	**Purchase**	**Assemble**
	Pressure Transducer	P-v & T-s Diagram
	Wiring for DAQ	Data Acquisition
		Labview Display

Table 11: Power System Manufacturing

Power System		
Print	**Purchase**	**Assemble**
Reduction Hub	LED strip	Power Check
	RGB Wire	Motor to LED wires
	DC Brushless Motor	Reduction Hub to motor

Table 12: Ignition System & Cart Manufacturing

Ignition System & Cart		
Print	**Purchase**	**Assemble**
	Air Compressor	Air Diffuser
	Tubing	Air Introduction into system
	Air Compressor Adaptors	Low load usage system
	Valve	Power System into wall
	Cart	Main Power cable
	Plywood Standing	
	Surge Protector	

7.2 Design Changes

The thing that we changed in the Brayton Cycle design is the heating element. The size was changed because it was too small to fit in the shaft, also we had to change the angles of the blades to make it rotate easier. First we ordered an air compressor and when we got it we saw that it's produce 60 psi of pressure so we had a meeting with Dr. Willy, and he recommended us to ordered a new one which has a 150 psi of pressure.

The original casing was a constant slope decrease in area in the compressor section. Upon request of the client, minimize irreversibilities while maintaining visibility. The current case that is under production implements visibility and efficiency with 3D printing. Adjusting the area reduction was performed via discrete diameter changes along the casing to fit all blade stages.

8. References

[1] Ecourses.ou.edu. (2018). *Thermodynamics eBook: Brayton Cycle*. [online] Available at: http://www.ecourses.ou.edu/cgi-bin/ebook.cgi?topic=th&chap_sec=09.1&page=theory [Accessed 26 Jun. 2018].

[2] Instrumart.com. (2018). *About Band Heaters | Instrumart*. [online] Available at: https://www.instrumart.com/MoreAboutCategory?CategoryID=5039 [Accessed 26 Jun. 2018].

[3] Web.mit.edu. (2018). *Brayton Cycle*. [online] Available at: http://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node27.html [Accessed 26 Jun. 2018].

[4] Cengel, Y. and Boles, M. (1989). Thermodynamics.

9. Appendix

9.1 Code for IT Thermo

```
T1 = 294.261
T2s = 355
T2 = 356.7
T3 = 400
T4s = 328.35
T4 = 336.8
p1 = 100
p2s = 200
p2 = 200
p3 = 200
p4s = 100
p4 = 100


s1 = s_Tp("Air",T1,p1)
s2s= s_Tp("Air",T2s,p2s)
s2 = s_Tp("Air",T2,p2)
s3 = s_Tp("Air",T3,p3)
s4s= s_Tp("Air",T4s,p4s)
s4 = s_Tp("Air",T4,p4)
v1 = v_Tp("Air",T1,p1)
v2s = v_Tp("Air",T2s,p2s)
v2 = v_Tp("Air",T2,p2)
v3= v_Tp("Air",T3,p3)
v4s = v_Tp("Air",T4s,p4s)
v4 = v_Tp("Air",T4,p4)
h1 = h_T("Air",T1)
h2s = h_T("Air",T2s)
h2 = h_T("Air",T2)
h3 = h_T("Air",T3)
h4s = h_T("Air",T4s)
h 4= h_T("Air",T4)
```

9.2 Bill of Materials

To Buy					$333.06		$96.26
Description	Part	Part #	Quantity	Location	Cost	Purchased (Y/N)	Actual Cost (with tax)
Shaft	3/4" - 24" Shaft K	1570K63	1	https://www.mcm	$47.40	Y	$41.68
Shaft		1497K31		https://www.mcmaster.com/#1497K31			
LED Strip	1ft RGB LED		1	https://www.solid	$14.00	Y	
Air Compressor	PowerSmart 4 ga	PS60	1	https://www.ama:	$74.67	N	
Generator							
Ball Bearings	1.25" Ball Bearing		3	https://www.grair	$4.50		$13.50
Heating Band	Tempco Heating	NHL00100		https://www.grain	$28.50	Y	$41.08
Heating band				https://www.grair	$32.30	N	
Thermal Fuse				https://www.ama:	$11.69		
Pressure acquistition							
Acryllic							
Printed Parts							
	Turbine 1		1	Rapid Lab	$10.00		$0.00
	Turbine 2		1	Rapid Lab	$10.00		$0.00
	Turbine 3		1	Rapid Lab	$10.00		$0.00
	Compressor 1		1	Rapid Lab	$10.00		$0.00
	Compressor 2		1	Rapid Lab	$10.00		$0.00
	Compressor 3		1	Rapid Lab	$10.00		$0.00
	Compressor 4		1	Rapid Lab	$10.00		$0.00
	Compressor 5		1	Rapid Lab	$10.00		$0.00
	Compressor 6		1	Rapid Lab	$10.00		$0.00
	Stator 1		1	Rapid Lab	$10.00		$0.00
	Stator 2		1	Rapid Lab	$10.00		$0.00
	Stator 3		1	Rapid Lab	$10.00		$0.00