



Design of a Stirling Engine for Electricity Generation

A Major Qualifying Project

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Abstract

The aim of this project was to design, build, and test a Stirling engine capable of generating between 200-500 watts of electricity. Several designs were studied before settling on an alpha type configuration based around a two-cylinder air compressor. Concentrated solar energy was considered as a potential heat source, but had to be replaced by a propane burner due to insufficient solar exposure during the testing timeframe. The heater, cooler, regenerator, flywheel and piping systems were designed, constructed, and analyzed. Instrumentation was built into the engine to record temperatures throughout the assembly. Several tests were performed on the engine in order to improve its running efficiency, and critical problem areas were isolated and addressed.

Acknowledgements



Thanks to Professor John M. Sullivan, our project advisor and mentor. Without his guidance and experience, this project could not have come together the way it did. Professor Sullivan's interest in the Stirling engine was a constant source of enthusiasm across the entire year. With his direction we were able to create a great project which was also enjoyable for the group. His supervision cannot go unnoticed and he was the main motivating factor across the term of the project.



Thanks to our close aide Peter Hefti who has been inspiring us since we began working with him to strive for the best results. He was a major help with torque calculations, temperature measurement technology, and experimental guidance. He was also of practical assistance in furnishing the MQP lab with all the equipment we needed. His assistance is deeply appreciated.

The group would also like to thank the lab staff at the Washburn machine shops, especially Aaron Cornelius for his assistance in machining the components of our engine.

Executive Summary

Our team, motivated by the need for new sources of renewable energy, designed and built a Stirling engine to function as an electric generator. Stirling engines operate on a regenerative thermodynamic cycle where the working fluid is enclosed within the engine. Fluid flow is modulated by changing volumes within the engine. The two pistons of the engine are exposed to a hot source and cold source, respectively. The working fluid compresses within the cold space, is transferred to the hot space, and expands to do work on the piston. A regenerator is placed between the expansion and compression spaces, which extracts and stores heat from the expanded air to preheat the cool working fluid. The team utilized SolidWorks and Esprit to design the engine components, and manufacturing was performed using Haas CNC tools.

This project focused on three broad goals. We identified the heat source that will be used to operate the engine, then determined the engine type suitable for that source and designed its main components. Lastly, we researched and sourced a generator to convert mechanical power into usable electric power.

After reviewing many sources of heat production, such as server rooms, power plants, and restaurant fryers, the team decided to use concentrated solar rays as our energy source. A Fresnel lens was chosen to concentrate the solar energy. Depending on the size of the lens, they can produce between 1000-2000 °F during the summer in areas near the equator. We obtained a Fresnel lens from a rear-projection TV, and framed it for stability in our tests. Multiple experiments with the lens were performed to establish a baseline power potential.

Our Stirling engine was built using a two-cylinder air compressor. After obtaining the compressor, we replaced the piston caps with custom made heating and cooling systems. A regenerator, flywheel, and connecting pipe were also installed. Internal temperatures were recorded by thermocouples placed throughout the system.

A suitable electric generator was also researched and purchased to convert the shaft output into electrical power. We prioritized finding a generator able to produce power at low RPM. After obtaining the desired generator, we determined through testing the required torque and RPM needed from the engine in order to produce power.

Numerous tests were run on the engine with full data acquisition. The experiments were performed in winter, with low available sunlight. A propane burner was substituted for the Fresnel lens as a result. Our tests revealed problems within the engine that prevented it from running. The first was too much dead volume, which was partially remedied by filling internal cavities with expanding foam. There was also a large amount of friction at the compressor output shaft, which did not improve even with the addition of oil. A leak on the hot side piston cap was also discovered, which proved impossible to fix due to the extremely high temperatures present. Numerical analysis of the engine also implicated the low pressure of the working fluid as a source of error.

Despite the obstacles encountered, the team gathered enough data to indicate the work done by the engine, and its capability should it be fixed. The team recommends future work be done in addressing the problems outlined above, with the end goal of pressurizing the working fluid to produce useful work. Further research into more advanced manufacturing techniques could also lead to improvements in design of the engine components, and reduction of dead volume.

Authorship

William Frankian was the design team leader, and assisted with all aspects of engine construction. He also designed and manufactured the regenerators and flywheel. He wrote the flywheel and regenerator methodology sections, and performed the numerical analysis calculations. He also wrote the introduction, background, and executive summary.

Gary Jackson designed the LabView program and assisted in testing the generator and engine. He assisted in building the frame for the engine and engine assembly. He was the author of the methodology, compressor, the temperature results, and conclusion sections.

Evan Stewart was the designer of the heater, connecting piping, and cooler base. He developed preliminary designs of the engine. He wrote the alternative designs of Stirling engine and Heater sections. He also created the CAD and CAM files used in fabrication, and headed fabrication of the heater and cooler base, and assisted in fabrication of the flywheel and cooler.

Alula Shiferaw assisted with the Fresnel lens experiment and data acquisitions, and analyzed some of the data we got from the experiment. He wrote the executive summary, the torque testing, and parts of the heat section.

Shawn Czerniak was the primary author of the section on the Heat Sources. He also acquired the Fresnel lens and tested it. He found the propane burner, and assisted in building and testing the engine.

Hongling Chen was the primary designer of the cooler and assisted in parts fabrication and engine testing. She was the author of the cooler and engine testing methodology sections.

Enrique De La Cruz assisted with the generator testing and was the author of the background, and secondary author of the generator section of the results and discussion. He also manufactured the preliminary designs for the cooler tank and helped with fabricating the engine.

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1.0 Introduction

The goal of any engine is the production of useful work. Most modern engines rely on internal combustion in some form to drive pistons and an output shaft. Internal combustion engines suffer from relatively poor efficiency and increasingly complicated electronic and mechanical systems. A Stirling engine avoids these problems. By having the working fluid stay inside the pistons through the entire engine cycle, it provides good operating efficiency, low complexity, and high versatility.

Dr. Robert Stirling developed the true Stirling engine design in 1816¹. Stirling's *heat economiser*, now known as the regenerator, drastically improved the efficiency of the closed-cycle air engine. The regenerator acts as a heat exchanger between the cold and hot sides of the engine, absorbing heat from the working fluid during the expansion stroke, and returning it during the compression stroke. This process allows for significant energy savings between cycles. Existing steam and hot air engines at the time could not compensate for this lost heat. The addition of the regenerator allowed the Stirling engine to enjoy a period of unrivaled efficiency. It was also significantly safer to operate than steam engines, as their boilers ran the risk of exploding. Soon, advances in steam engine design, and later internal combustion, eclipsed the Stirling engine in terms of practicality and efficiency. It became much cheaper to produce high-horsepower steam engines because of advances in materials and boiler construction, and internal combustion engines soon became ubiquitous in cars.



Figure 1 Rev. Dr. Robert Stirling

¹ R. Stirling, Improvements for diminishing the consumption of fuel and in particular, an engine capable of being applied to the moving of machinery on a principle entirely new. British Patent 5456 (1817)

Today, the engine is receiving renewed interest as a means of generating electricity. Emphasis on sustainable energy has brought attention to the engine's ability to convert a wide variety of heat sources, such as focused sunlight and waste heat, into mechanical work. Figure 2 shows a solar concentrator whose parabolic dishes are focused on the expansion cylinder of a Stirling engine. This station alone is capable of generating 25 kW in full sunlight, enough to power a mid-sized house. The engines can also be retrofitted to existing power stations, where they can scavenge waste heat from the cooling systems to generate electricity.



Figure 2: Stirling engine in conjunction with solar concentrator

A Stirling engine is a reversible system; given mechanical energy, it can function as a heat pump or cooling system. Below -40°C , there are no refrigerants suitable for use in a Rankine style cooler. Since the Stirling engine relies only on the input of mechanical energy to supply a temperature gradient, it is a highly competitive method of cooling in the cryogenic market. Similarly, a heat pump using a Stirling system takes advantage of the developed temperature gradient to move ambient heat from the environment into a space, such as a building.

Stirling engines have also been proposed for use in space applications. Their relatively simple construction and high degree of versatility make them ideal for long-term use on deep space probes². Additionally, they do not produce any exhaust or waste which would disrupt a satellite's flight.

² Mann, Adam. "New Nuclear Engine Could Power Deep-Space Exploration" *Wired*. November 27th, 2012.

2.0 Background

The Stirling Cycle

Stirling engines exhibit the same processes as any heat engine: compression, heating, expansion, and cooling. Stirling engines operate on a closed regenerative thermodynamic cycle. Gas is used as the working fluid, and undergoes cyclic compression and expansion in separate chambers with changing volume. In a typical Stirling engine, a fixed amount of gas is sealed within the engine, and a temperature difference is applied between two piston cylinders. As heat is applied to the gas in one cylinder, the gas expands and pressure builds. This forces the piston downwards, performing work. The two pistons are linked so as the hot piston moves down, the cold piston moves up by an equal distance. This forces the cooler gas to exchange with the hot gas. The flow passes through the regenerator, where heat is absorbed.

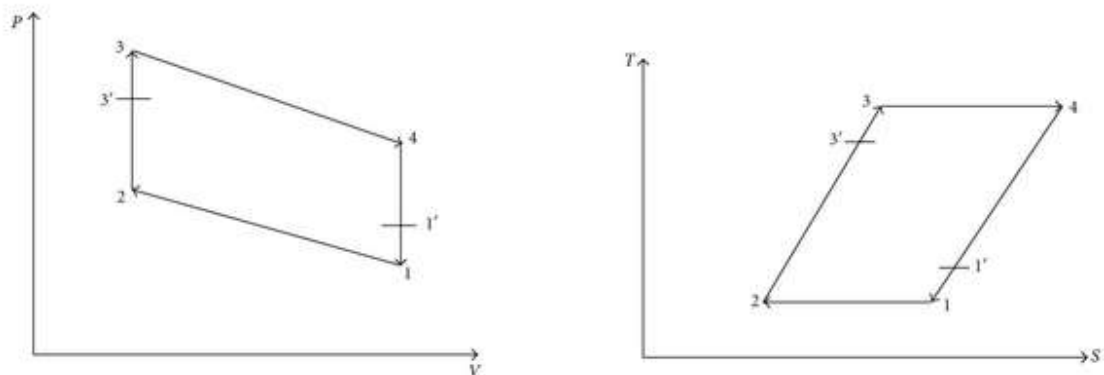


Figure 3: Ideal Pressure-Volume and Temperature-entropy charts of the Stirling cycle.

The Stirling engine approximates the idealized thermodynamic process shown in Figure 3 above, known as the Stirling cycle³:

³ Asnaghi et. al. "Thermodynamic Performance Analysis of Solar Stirling Engines". 2 May 2012, REDEER center, Tehran, Iran. < <http://www.hindawi.com/journals/isrn.renewable.energy/2012/321923/>>.

1. Process 1-2: Isothermal compression. One piston compresses the working fluid within the compression volume, while the other is stationary. This increases the pressure of the system at a constant temperature.
2. Process 2-3: Isochoric transfer I. Both pistons move in opposition (90° out of phase) to transfer the working fluid from compression to expansion volume. The regenerator, in an ideal situation, raises the fluid temperature to $3'$ using heat stored from process 4-1. External heat supplies the remainder.
3. Process 3-4: Isothermal expansion. The expansion piston is moved by the expanding fluid, which is maintained at a constant temperature by the external heat source. Work is done in this stage on the piston by the working fluid.
4. Process 4-1 Isochoric transfer II. The reverse process of 2-3, both pistons work to transfer the fluid from the expansion to the compression space. The regenerator absorbs heat from the fluid, reducing the fluid temperature to that at $1'$.

Alternative Designs for Stirling Engines

As with all hot air engines, Stirling engines require that their heat sources and sinks are oriented to ensure a sufficient volume of the working fluid is heated and cooled at the appropriate point in the cycle. These orientations have been worked into several different engine design types, designated alpha, beta, and gamma⁴. All of these engine types follow the Stirling cycle, and share the same basic components, but differ in how they are constructed.

Alpha type engines are distinguished from the other designs by the method of separation of the hot expansion chamber and the cold compression chamber. In an alpha type engine the hot

⁴ "Stirling Engines - Mechanical Configurations." *Ohio University*. N.p., Apr. 2010. Web. 23 Mar. 2014. <<http://www.ohio.edu/mechanical/stirling/engines/engines.html>>.

and cold chambers are distinctly separated from one another, usually in separate cylinders. One cylinder is for expansion and the other is for compression. The pistons are linked to the same crankshaft. The two piston volumes are linked through a pipe or some likewise component, with the regenerator placed in the path of the fluid between them.⁵ This configuration makes an alpha type engine the simplest Stirling engine design to work with, since the clear separation of the heat source and sink prevents any premature mixing of the hot and cold working fluid. This ensures that the expansion and compression cycle can continue unabated. One concern with this design is that the need for connections between the pistons increases the number of required parts. This results in an increased chance of leakage around joints and connections. This is especially true on the expansion chamber where the intense heat can cause leaks to form.

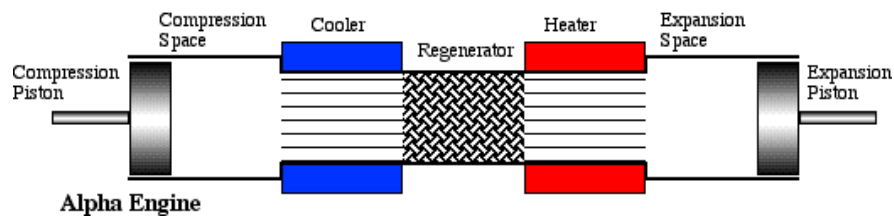


Figure 4: Simplified version of an Alpha type Stirling engine

Beta type engines are distinguished from alpha types by the lack of separate chambers for the hot expansion and cold compression stages of the cycle. In a beta type, the expansion and compression actions are performed in the same cylinder with only a single piston to derive power from the engine. A displacer, which is a loosely fit non-sealing piston, is also inside the cylinder in line with the power piston. The displacer serves to force the working fluid to flow around it and between the expansion and compression sections of the cylinder. As the working fluid expands and contracts, it drives the power piston, which in turn drives the displacer, restarting the cycle. Beta type engines have the benefit of not having a hot seal, since the only seal in the

⁵ Keveney, M. "Two Cylinder Stirling Engine." 2000. <<http://www.animatedengines.com/vstirling.html>>

system is around the power piston in the compression section of the cylinder. As a result leaks are much easier to contain. A concern though with this design is that with heating and cooling occurring in the same cylinder, regulating interference between the cycles is more difficult.

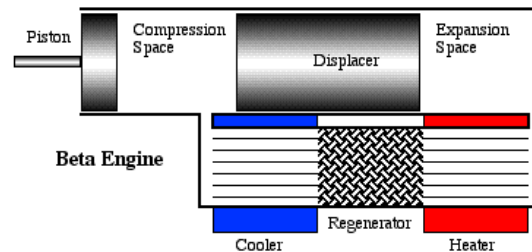


Figure 5: Simplified image of a Beta type Stirling engine⁶

Gamma type engines function similarly to beta type engines, with the hot expansion and cold compression stages occurring in the same cylinder and a displacer forcing the working fluid to flow between the sections. They are distinguished from beta types since the power piston in gamma type engines is not located in line with the displacer. The power piston is located in a separate cylinder that is connected to the compression section of the initial cylinder. This configuration allows the power piston to not be limited by the displacer orientation or size. Gamma type engines have the same benefits as beta types in avoiding hot seals, and the same concerns with regulating interference between the cycles. The additional cylinder in gamma types means more dead volume, or working fluid that is not contributing to the expansion or compression stages. This results in a low compression ratio and lower possible power output.

⁶ "Beta Type Stirling Engines." *Ohio University*. N.p., Apr. 2010. Web. 23 Mar. 2014. <<http://www.ohio.edu/mechanical/stirling/engines/beta.html>>.

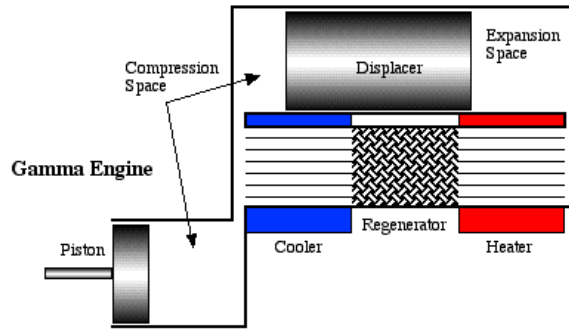


Figure 6: Simplified version of a Gamma type Stirling engine⁷

Green Power Applications

Since the Stirling engine works on a temperature differential, any heat source can be used to power the engine. The size of the Stirling engine can also be adjusted to optimize the energy recovered from the heat source. Man-made or naturally occurring energy sources are potential resources that could be used in conjunction with a Stirling engine. When considering man-made options, the main goal is to scavenge the heat produced by other systems and convert it to useful mechanical or electrical energy. Server rooms in particular are an emerging source of waste heat. The electronics in these rooms generate massive amounts of heat, which have to be dispersed appropriately. Modern server rooms use large fans and resource-intensive cooling systems to remove the heat. An application for a Stirling engine in this case would be capturing heat from the return air ducts or out from the cooling fluid, and returning that lost energy to the grid or directly to the servers. A similar application can be used in many industrial sites. Some companies, such as CoolEnergy, currently apply Stirling engine technology for waste heat recovery⁸.

⁷ "Gamma Type Stirling Engines." *Ohio University*. N.p., Apr. 2010. Web. 23 Mar. 2014. <<http://www.ohio.edu/mechanical/stirling/engines/gamma.html>>.

⁸ Cool Energy Inc. "SolarHeart Engine Diesel Genset Waste Heat Recovery" 2012

Geothermal or hot spring locations offer a naturally occurring temperature differential. Placing the hot chamber of the Stirling engine inside a hot spring would be an easy way to gather the heat necessary to keep the engine running, as long as a cooling system was maintained. Geothermal heat does not require any specific location for utilization, because at a certain depth the Earth is a constant temperature. Geothermal Stirling engines could be used in areas without easy access to the grid, and function as either heat pumps or as generators.

Generator

A Stirling engine requires an electric generator to convert its mechanical output into electricity. Generators ranging from low to high voltage outputs, alternating or direct current are available. They are usually purpose built for different design applications, such as wind power, hydroelectric, solar, nuclear and fossil-fuel power generation.⁹

Generators convert mechanical energy into electrical energy by using a center rotor that is surrounded by stator magnets, which create a magnetic field. These rotors interact with either an electromagnet or a permanent magnet to generate electric current.¹⁰ The current that is produced can come in either direct current (DC) or alternating current (AC). DC flows constantly in a unidirectional fashion, which can be seen in Figure 7. This type of current is generated by having a commutator or switch that enables the flow of current to reverse itself every time the electrical cycle is completed, which then produces the direct current flow. On the other hand,

⁹ U. S. Department of the Interior. Reclamation: Managing Water in the West: Power Resources Office, 2005, pg 6. Hydroelectric Power. Web. 25 Mar. 2014.

¹⁰ Chan, Tze Fun and Lai, Loi Len “Sustainable Energy & Development” 200, Page 21

alternating current has the ability of retracting back and forth in the circuit by switching the polarities of the magnet rotating in the magnetic field.¹¹

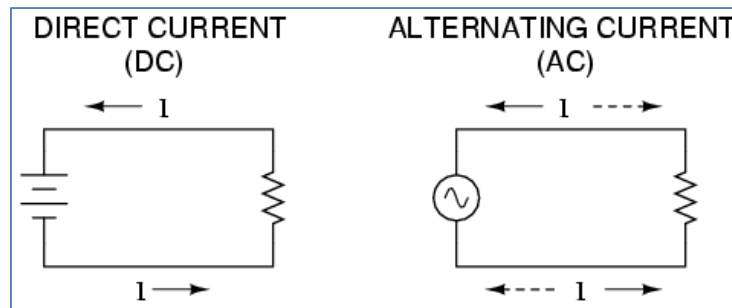


Figure 7: Difference in current direction between AC and DC circuits

Both AC and DC generators are very effective but depending on what application the generators are going to be used in can have detrimental effects. An AC generator is able to transfer the electricity much further and safer than DC.¹² Since DC current travels at a constant rate, after a given distance, the power rating will begin to diminish therefore not being an efficient way to transmit electricity.

Permanent Magnet Generator

Although there are many types of generators in the industry, the permanent magnet generator (PMG) is the best choice in terms of achieving low friction, high efficiency, compact sizes, light weight and robustness.¹³ Their low friction design enables a machine to convert mechanical energy into electrical energy with little resistance. PMG's are often seen in wind turbine power generation but can also be retrofitted to work with almost any other application.

¹¹ Elliott, Brian S. "1.6 Alternating Current (AC)." *Electromechanical Devices & Components Illustrated Sourcebook*. New York: McGraw-Hill, 2007. Print.

¹² AC vs DC (Alternating Current vs Direct Current)." *Difference and Comparison*. Web. 26 Mar. 2014.

¹³ Nasiri, A.; Zabalawi, S.A.; Jeutter, D.C., "A Linear Permanent Magnet Generator for Powering Implanted Electronic Devices," *Power Electronics, IEEE Transactions on*, vol.26, no.1, pp.192,199, Jan. 2011

These generators have been accepted more in the industry over the recent years.¹⁴ This is because PMG's are relatively easy to maintain and provide a reliable results. Their reliability is due to the incorporation of brushless designs and the removal of rotor windings. Permanent magnet generators have several components that make these generators as efficient as they are. The main parts include the stator, which is the stationary steel body, a rotor that contains the permanent magnets and an electrical wire or armature to transfer the generated electricity, as shown below in Figure 8. As the rotor rotates about its axis, the generator will begin to produce a voltage, thus a permanent magnet generator.

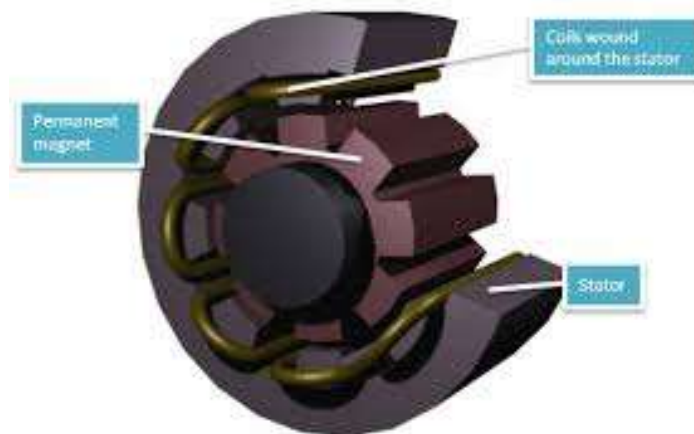


Figure 8: Permanent Magnet Generator components¹⁵

¹⁴ Chan, Tze Fun and Lai, Loi Len "Sustainable Energy & Development" 200, Page 23

¹⁵ Littmarck, Fanny. "COMSOL Blog." *Simulating Permanent Magnet Generators*. COMSOL, 6 Nov. 2012. Web. 27 Mar. 2014.

3.0 Methodology

Design of the Stirling Engine

Our project began with researching the history and design of existing Stirling engines. While a relatively large hobby building community exists, few designs for engines of practical scale have been proposed. We built a small-scale engine to examine the principles of Stirling engine construction and operation. Our main design inspiration came from an engineer who built an engine to operate in the 500-700 Watt range¹⁶. This engine used a propane burner as its heat source. Our design was intended to be more versatile, with the intention of using concentrated solar power as the heat source. One of our goals was to keep the engine easily modifiable, while still maintaining good dimensional tolerances and component compatibility. We decided to utilize as much of the existing air compressor as possible in order to reduce the amount of time needed for construction.

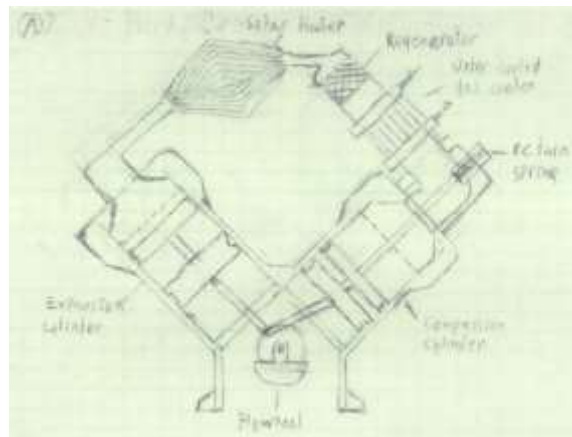


Figure 9: Preliminary Design Sketch

¹⁶ Kirk, David. "The SV-2 Stirling Engine Project". DIY Stirling Engines. < <http://diystirlingengine.com/sv-2-stirling-engine-generator/>>

Compressor

A key design innovation was the adaptation of the piston housing of a V-block air compressor into an engine. We considered this a good design choice as opposed to machining our own pistons and housing. Not only would the tolerances required by the design be difficult to achieve on the machines available, we felt that engineering a two-cylinder V-block piston assembly was beyond the timeframe of our project. We sourced a Chrysler RV2 compressor from O'Reilly Auto Parts. The compressor was received unused, and can be seen in Figure 10.



Figure 10: Compressor used for pistons of the Stirling engine

We removed the caps covering both of the pistons in order to investigate how we could convert the compressor into a Stirling engine. Figure 11 shows an internal view of the piston once the caps on the engine were removed. With the removal of the caps and noting the inner workings of the compressor, we concluded that one cap could be used as part of the cooler. The heater would need to be completely rebuilt in order to get the material properties needed. Of the seven boltholes that can be seen in Figure 11, all seven are used to connect the modified cooler cap, while only four were necessary to connect the heater. The oil inside the compressor was also replaced with a 5W-50 motor oil in order to assist the movement of the pistons and reduce the friction inside the pistons and on the crankshaft.



Figure 11: View under the caps of the compressor

The interconnecting chambers of the compressor, which appear as rounded rectangles in Figure 11, were used to place thermocouples throughout the system. These four thermocouples were placed such that they could be used to measure the temperatures at the tops of both the hot and cold pistons, and inside the regenerator. After these thermocouples were placed and had the correct length we filled the rest of the empty space to make sure that the airflow created by the pistons would stay inside the piping and create the cycle needed in order to run the engine.

Heater

The operation of a Stirling engine requires that a working fluid in a closed system is both cooled and heated to induce the expansion and compression cycle. The thermal energy that is introduced into the system is done so in the expansion cylinder of the engine, using a heater. The heater in any Stirling engine design must meet several requirements. First is the ability to transfer heat through either itself or the cylinder wall and into the expansion cylinder without significant losses. It must also be able to maintain a closed seal on the working fluid system, and to limit accidental heat transfer into sections of the engine outside the expansion cylinder.

The design of the heater is dependent on the type of Stirling engine. Alpha and Beta type Stirling engines have heating sections that are separate from the rest of the engine body, and thus have some freedom with the heater positioning and design. Gamma engines, since their heating and cooling systems have to be in line with each other, have limited possible designs for their heaters. This information inclined us to focus on an appropriate heater for an alpha type engine.

In an alpha type engine the heater is usually positioned either on top of the hot piston so that the air has to flow through the heating area into an insulated expansion cylinder, or along the walls of the expansion cylinder themselves. The difficulty in choosing the orientation of this component comes from having to balance having the highest possible area for heat transfer while also having low dead volume in the system. If the dead volume is minimal but there is almost no heating area then no heat transfer can take place, and if the dead space is too large then the required heat transfer would increase substantially. Since we had chosen to base our engine off a dual piston V-block, we were limited to using a heater that is heating air traveling into the hot side rather than heating the chamber itself. This is due to the compressor being made of cast iron, which has a fairly low thermal conductivity and makes heat transfer across it into the expansion cylinder difficult. Our heater, therefore, had to be positioned on the opening of the expansion

cylinder and made of a material with a higher thermal conductivity than cast iron to provide the most heat transfer to air entering the cylinder.

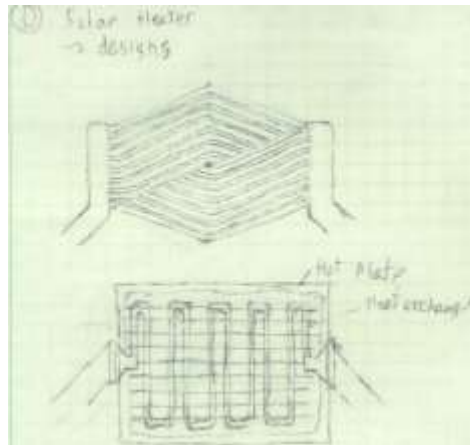


Figure 12: Preliminary Heater Design Sketches

The compressor caps held a one-way valve on the ends of each cylinder chamber. While the initial design, as shown in Figure 12, was external to the compressor cap, a desire to limit dead space led us to replace one of the original caps with the heater. For simplicity, we used the same bolt pattern as the original cap when designing our heater. The preliminary design was a simple extension of the expansion cylinder into an open chamber, with an exit hole on the side facing towards the cooler for the piping. The top of this chamber would be sealed with a thin copper plate nested into an indent and held in place by bolts. The copper would serve as our heat transfer area and covered enough space to be a viable position for the Fresnel lens to focus on. copper was selected for its high thermal conductivity. We discarded this design due to several factors, firstly the size of the chamber was too large and created too much dead volume, and secondly the copper plating that we had available warped during high temperature testing, as seen in Figure 13.



Figure 13: Warped heater plate

Our redesign accounted for these problems by first reducing the volume of the heater and secondly by replacing the copper plate. The general shape of the heater remained the same except we choose a basic rectangle base instead of the compressor base, which reduced the height of the part to .75 in from 2 in. This change reduced the volume of the part significantly from 18.18 in³ to 7.27 in³. For the heat transfer plate, we selected an aluminum plate with a thickness of 0.125 in. Aluminum alloy 6061 has a lower thermal conductivity than copper, at 180 W/mK compared to 400 W/mK. However, this was still sufficient for our purposes, and in testing it did not warp like copper. This redesign also forced an alteration of the position of the hole for the exit pipe. The reduced height of the part meant that the diameter of the pipe (1.125 in) was too large to exit from the side. We decided to reposition the hole so that the pipe exited normally from the heat transfer plate and then angled 90 degrees away.

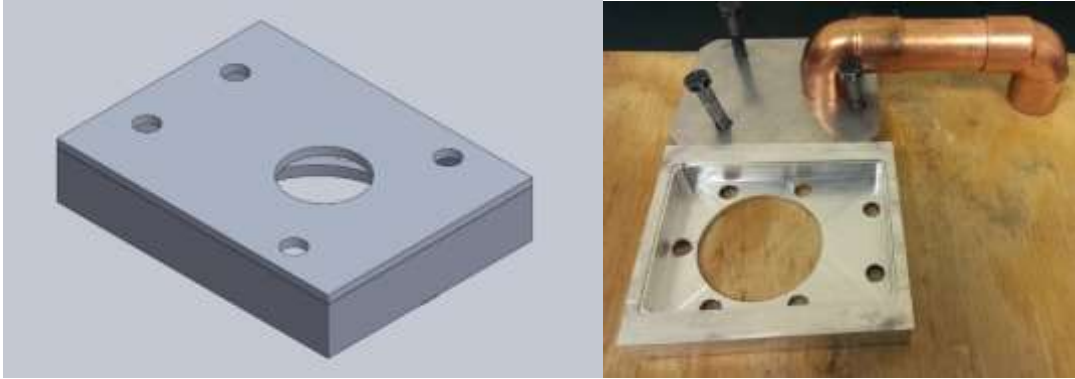


Figure 14: Heater CAD Model and Completed Component

Construction of the heater was achieved over several machining operations in which we pocketed out the internal volume of the new cap, bored the opening to the expansion cylinder, and drilled the holes for the piping and bolts. As a final modification to our design after construction had finished we used aluminum foil as sealant between the heat transfer plate and the cap, and around the piping entering the heater. The foil acted as a high temperature resistant form of Teflon tape as most other adhesives and sealants cannot sustain the temperatures encountered during anticipated steady state operation.

Regenerator

The regenerator was Dr. Stirling's principal contribution to the field of hot air engines. The intent of a regenerator in a Stirling engine is to recover as much heat as possible from the air coming out of the expansion cylinder. As the hot working fluid expands, it flows through the regenerator coil. The coil removes and stores some of the heat from the air before it passes through the cooler. This allows for reduced energy requirements for the cooling of the fluid. The opposite is true on the return stroke. The regenerator returns the stored heat to the cooled fluid, therefore making the engine import less energy to heat the fluid up again. This regenerative action is the reason Stirling engines have high thermal efficiencies between given temperature

limits¹⁷. Regenerators also have an advantage over other methods because of their high surface area to volume ratio, which requires less material to manufacture.

The design of our regenerator focused on maximizing the surface area. Our original design was similar to existing mesh-type regenerator systems. It consisted of a packed mesh of steel wool, with a known porosity. However, one of the drawbacks of the regenerator system is that consistent and turbulent temperature fluctuations can put a lot of stress on the regenerative material. Coupled with the pressure of air flowing back and forth, this can lead to significant degradation. Over time, pieces of the steel wool could fall into the piston cylinders and cause damage to the walls. After multiple issues with the steel wool becoming frangible under high heat, the mesh type design was abandoned.

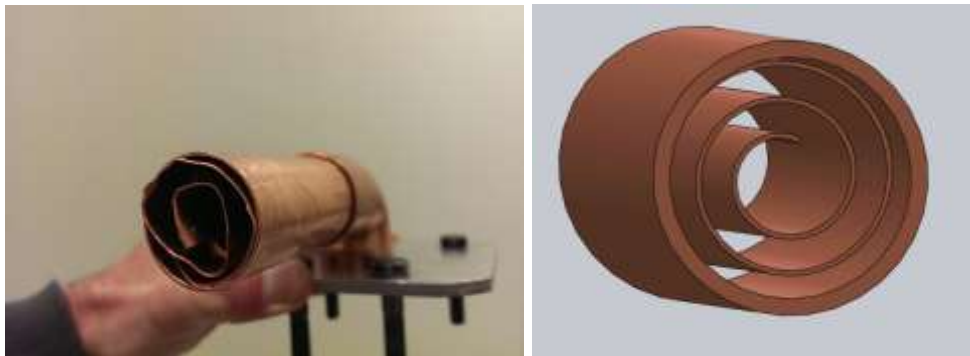


Figure 15: Regenerator CAD Model and Completed Component

The regenerator was redesigned as a copper coil. This was settled on due to ease of construction and low impedance to fluid flow, while maintaining good surface contact area. Copper was chosen as the regenerator material because of its high thermal conductivity, which would allow for quick absorption and release of stored heat at the high RPM expected in the engine. A thin copper sheet was used, and holes were cut in it to maximize the exposed surface area. As shown in Figure 15, the sheet was coiled by hand and fit inside each pipe section.

¹⁷ Walker, G. The Stirling Alternative: Power Systems, Refrigerants, and Heat Pumps. 1994.

This achieved the dual purpose of reducing dead volume and improving the surface area coverage for heat absorption and return.

Upon testing, the thermocouples inside the pipes recorded a definitive temperature gradient within the regenerator sections between the heater and cooler. This is a strong indication that the coils are effectively absorbing heat. The numerical analysis section of this report provides more detail on the thermodynamics within the regenerator.

Cooler

The main purpose of the Stirling engine cooling system is to provide a sufficiently low temperature consistently to keep the cycle running. In order to meet the design intent of the alpha type Stirling engine, our cooler is designed as an external system. The cooler is an ice tank that sits on top of the engine cap; the airflow piping comes from the bottom of the cooler and exits through a sidewall.

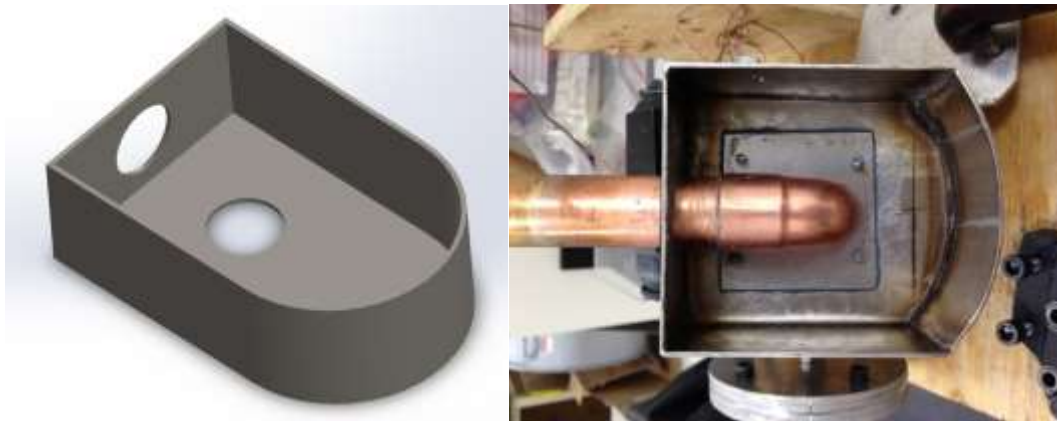


Figure 16: Cooler CAD Model and Completed Component

The original cooler CAD model was created in SolidWorks to accommodate the piping and engine cap dimensions, as seen in Figure 16. The cooler tank was made out of a sheet of stainless steel and welded into a tank shape. A hole was cut into the bottom center and one hole cut on the sidewall to fit the airflow piping and elbows. Silicone gasket sealant was then placed between the copper pipes and the tank to eliminate leaks and secure the pipes in position.

Since the cooler tank was fabricated as an open top structure, we decided to make a cover to prevent leakage. After some research and discussion, we agreed that a stretchable rubber mat attached to the cooler with Velcro tape would be a suitable choice. Using Velcro tape allows the cover to be removed whenever we need to add ice or when we need to take off the cooler cover and make adjustments. From the heat transfer aspect, the cover helps insulate the cooler and keeps the ice inside from being affected by ambient temperature changes. The cover would also contain the coolant if the engine were tilted for different tasks.



Figure 17: Cooler Cap

Before testing our prototype engine, we first tested out each individual component that made up the engine. The cooling system passed the test without any water leakage and the rubber mat was firmly secured via Velcro tape. Unfortunately, since our tests required the use of a propane burner rather than the sun, the cover was removed to reduce the risk of melting or fire.

After the prototype engine testing, the cooler tank performed well; temperature recordings indicated it began at around the freezing point of water. The cooler temperature gradually rose over a period of about 10 minutes as heat was exchanged from the pipe. Gains in cooling efficiency could be realized by keeping the coolant flowing continuously across the cold region of the engine. The other method could be using dry ice as a substitute for ice, which has a much lower sublimation temperature, and would create a higher temperature difference.

Flywheel

The flywheel of a Stirling engine stores some of the mechanical energy generated in the power stroke of the cycle, and returns it to the crankshaft when the pistons reach their full extension. This overcomes the locking up of the pistons and allows for continuous motion within the engine.

The design of the flywheel began with the need to produce a flywheel that can store enough energy to overcome the measured torque required to start the engine. As measured during our tests, the engine required an average of 7.8725 inch pounds of torque. Therefore a flywheel capable of producing more than that amount is required. For practicality of manufacturing, and ease of configuration, we utilized several disks of 6061 aluminum. The disks were bolted together, and another bolt was used to attach the assembly to the output shaft of the engine. The connecting bolt was secured by lock nuts. A small gear was attached to allow for power transmission to the generator.

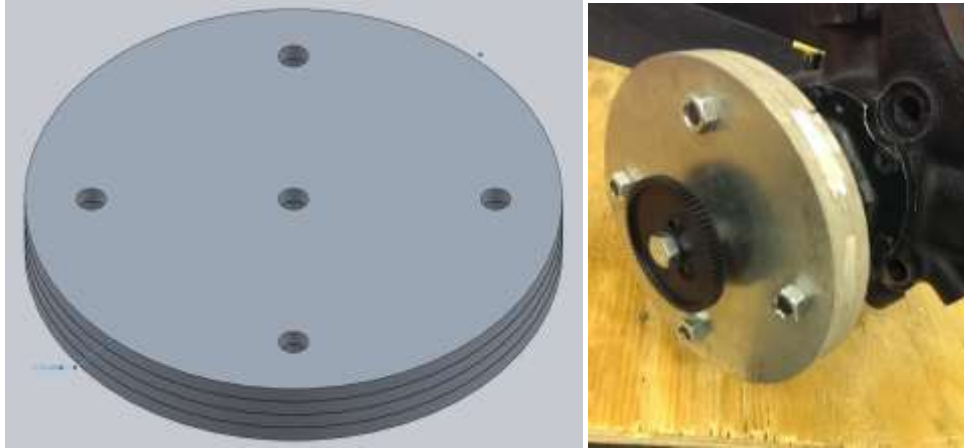


Figure 18: Flywheel CAD Model and Completed Component

Two basic equations define how much energy the flywheel imparts to the shaft. For this project, our flywheel weight was 1.66 lbs., with a radius of 2.725 inches (.227 ft.). Our tests brought the flywheel up to a maximum of 1150 RPM. It can be seen that we achieve 26-inch pounds of torque when rotating the flywheel at 1150RPM, giving us more than three times the torque required.

The moment of inertia of the wheel (I) is

$$I = kmr^2$$

Our flywheel can be approximated as a solid cylinder, so $k=1/2$. Therefore:

$$I = \frac{1}{2} * 1.66 * 0.227^2 = 0.043 \text{ lbf} * \text{ft}^2$$

The kinetic energy of the flywheel (E_f) is

$$E_f = \frac{1}{2} I \omega^2$$

The angular velocity $\omega = 1150 * \frac{2\pi}{60} = 120.43 \text{ rad/s}$. Therefore:

$$E_f = \frac{1}{2} * 0.043 * 120.43^2 = \mathbf{311 \text{ lb} * \text{ft}}$$

At the highest RPM value, our flywheel stores more than enough energy to overcome the startup torque requirement, and is capable of returning the pistons from full extension to complete the Stirling cycle.

Instrumentation

In order to test our Stirling engine, we needed accurate temperature data from discrete areas of interest. We used thermocouples to address this. Figure 19 shows the internal thermocouple setup. Two type K thermocouples were used, one in the hot piston volume, and one in the hot side of the regenerator. Type K was preferred for this application because of their high temperature resistance. Three type T thermocouples were also used, one directly immersed in the coolant, one in the cold side of the regenerator, and one in the cold piston volume.

The thermocouples were threaded through the vestigial air outlet in the compressor, which were then sealed with expanding foam and JB Weld to reduce internal dead volume.

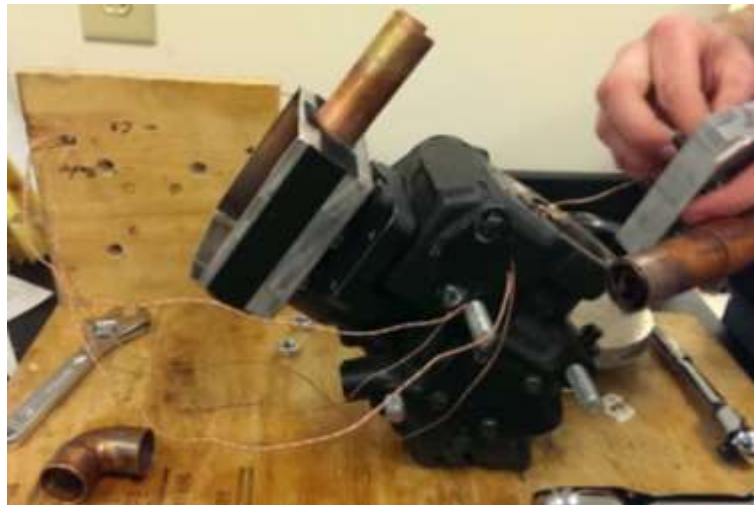


Figure 19: Assembly of internal instrumentation

After placing the instrumentation, we needed a program to record the data in real time and save the information for us to view and analyze later. We utilized LabVIEW to create a Virtual Instrument to read the thermocouple data. This program can be seen in Appendix C.

Heat Sources

We researched several renewable solutions for providing the heat our engine would require. Our preliminary list included 13 possible heat sources we would potentially tap into. After weighing the pros and cons of each, we decided the Fresnel lens was our best choice.

One of the potential heat sources we considered was the parabolic dish. The parabolic dish has the potential to reach temperatures over 200 degrees Celsius.¹⁸ It is also versatile. Depending on the design of the dish, the size of the focus as well as focal length can be optimized. These are great attributes for a solar collector.

Another possibility was a solar furnace. Similar to the parabolic dish, small-scale versions of the solar furnace can reach over 150 degrees Celsius. While these devices are somewhat commercially available, we were unable to find one that was the right size for our purposes.

The heat produced in a server room was another possibility. While these rooms usually reach temperatures of only 95 degrees Fahrenheit¹⁹, they produce consistent heat. The consistency is important because the Stirling engine only relies on the differential to produce energy, not necessarily high temperature. This option was eliminated because we did not believe our engine design could generate effective power at those temperatures. We also lacked reliable access to an appropriate testing environment.

The waste heat from a commercial deep fryer was also discussed. At the Frito-Lay Plant in Binghamton, New York, they are able to recover up to 160 degrees Fahrenheit from their

¹⁸Folaranmi, Joshua. "Design, Construction and Testing of a Parabolic Solar Steam Generator." *Leonardo Electronic Journal of Practices and Technologies (LEJPT)* 14 (2009): 115-33. 2009. Web. 12 Oct. 2013. <http://lejpt.academicdirect.org/A14/115_133.htm>.

¹⁹ Miller, Rich. "Too Hot for Humans, But Google Servers Keep Humming." *Data Center Knowledge*. N.p., 23 Mar. 2012. Web. 12 Oct. 2013. <<http://www.datacenterknowledge.com/archives/2012/03/23/too-hot-for-humans-but-google-servers-keep-humming/>>.

frying process.²⁰ However, this is a low grade heat of varying temperature, and would not maximize the effectiveness of a Stirling engine.

We also considered electronics, which produce waste heat through their own operation. A laptop can produce a large amount of heat while it is running, but this is often inconsistent. The power adapter from a laptop was also discussed because it stays hot almost any time the laptop is on. It also is small, portable, and could potentially be easy to harness. Light bulbs are another product which release a fair amount of consistent heat. They are seen everywhere which could make it a good application for a wide variety of locations. We considered the back of a refrigerator as well because this too would have consistent heat that could be tapped into. While these are each viable heat sources, they would require a low temperature differential engine and would not see a good amount of power removed.

The final route we considered but eventually passed on was geothermal. If it could be harnessed it could be a great heat source due to its consistency and availability. However, for the purposes of this project it would be difficult to tap into and therefore was decided against.

After eliminating many of the above options, we decided to use a Fresnel lens as our heat source. This solar concentrator is usually made from an acrylic resin, which allows for a long lifetime and also allows it to be transparent to most wavelengths of light in the solar spectrum.²¹ The Fresnel Lens is also cost effective thanks to its cheap manufacturability and has been proven by the test of time as its been used successfully for other purposes for centuries.

²⁰ "Fryer Exhaust Heat Recovery (ST7380-1)." *NYSERDA*. N.p., 27 Apr. 2011. Web. 12 Oct. 2013. <<http://www.nyserra.ny.gov/BusinessAreas/Energy-Innovation-and-Business-Development/Research-and-Development/Research-Project/Research-Projects/Research-Project-Search-Results/Project-Information.aspx?p=4381>>.

²¹ Leutz, Ralf, Akio Suzuki, Atsushi Akisawa, and Takao Kashiwagi. "Design of a Nonimaging Fresnel Lens for Solar Concentrators." N.p., 1999. Web. 12 Oct. 2013.

Fresnel Lens

In 1748, Georges-Louis Leclerc de Buffon came up with the idea to create a lens composed of several concentric circles as a way to reduce weight. Sometime later in 1821 this idea was improved upon by Augustin-Jean Fresnel as a way to create lighthouse lenses.²² Originally, the lens was used to take a small light source and magnify it to go large distances. As can be seen from Figure 20, this was a highly effective technique, and has remained relatively unchanged since its invention. When researching techniques for solar collection the Fresnel lens seemed to be a viable option for harnessing sunlight as a heat source.

The Sun is a major source of power. It produces approximately 90,000 TW of power annually, and most of this energy is lost to space or is not taken advantage of on Earth²³. Our goal was to use the Fresnel lens to take light from a large area and concentrate it into a smaller point. One of the modern applications for a Fresnel lens is in rear projection televisions. Inside the television the picture is created and reflected off a mirror across from the lens. The lens then takes the image which comes in at various angles and projects it as one flat image.

²² "Fresnel lens." Encyclopaedia Britannica. Encyclopaedia Britannica Online Academic Edition. Encyclopædia Britannica Inc., 2014. Web. 25 Feb. 2014. <<http://www.britannica.com/EBchecked/topic/219816/Fresnel-lens>>.

²³ Tsao, Jeff, Nate Lewis, and George Crabtree. "Solar FAQs." *Sandia National Laboratories*. N.p., 20 Apr. 2006. Web. 23 Mar. 2014. <<http://www.sandia.gov/~jytsao/Solar%20FAQs.pdf>>.

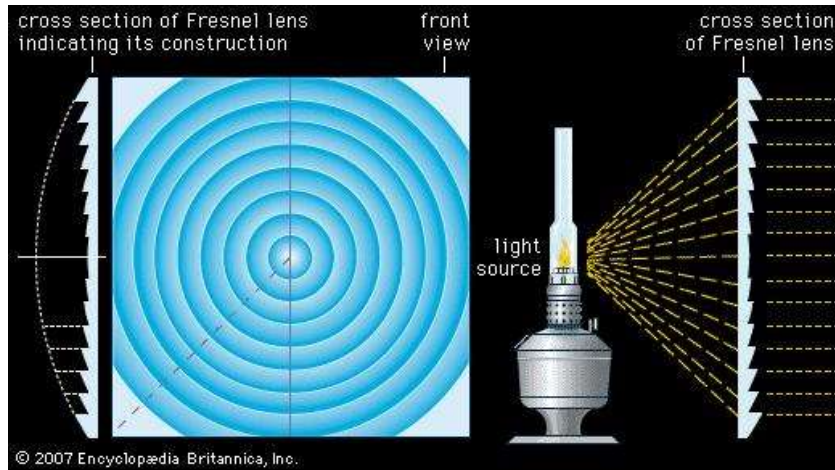


Figure 20: View of how a Fresnel lens works

As a first step to determine how much power we could get from a Fresnel lens we first had to acquire one. Thanks to their production in many rear projection televisions we were able to utilize Craigslist to find an old TV that had been replaced by a newer model. After getting the TV it was a relatively simple process to remove the lens. We then put the lens inside a wooden frame so we could easily maneuver it for testing.



Figure 21: Rear Projection TV (top left), Removing Outer Frame (Top Right), Outer Frame Coming Off (Bottom Left), and Fresnel lens Removed (Bottom Right).



Figure 22: Fresnel Lens in its frame

Lens Experiments

In order to determine the potential of the lens we first had to come up with an experimental procedure to create consistent testing data. We first determined what materials we would need for the experiment. These included 1 Fresnel lens, 1 Type K Thermocouple, 1 Omega HH506R Digital Thermometer, 1 glass jar, and 6 fluid ounces of water. A procedure was developed to conduct our experiments as itemized subsequently.

- 1) The glass jar was spray painted black to increase the amount of light energy it would absorb.
- 2) Fill the jar with 6 fl. oz. of water.
- 3) Adjust Fresnel lens to find the focal point



Figure 23: Sun Projection Measurement

- 4) Place jar within the focal area and place the thermocouple within the jar.



Figure 24: Lens Support and Heating Testing

- 5) Record the temperature of the water in 15 second intervals using the thermocouple



Figure 25: Heat Measurements Taken with Thermocouple

Overall, the tests we ran with the lens were successful. We were able to determine power output and efficiency. We were also able to calculate losses through our experiments. We used this information in conjunction with online data to determine what our system would require to run successfully. These results will be discussed in further detail in following sections.

Propane Burner

As discussed in the results section, we were unable to generate sufficient energy from our lens during the winter in Worcester. This led us to seek out alternative heat sources to simulate the power of the lens. We decided upon a concentrated propane burner as our testing heat source. We purchased the burner as well as the propane tank hose attachment through Amazon.com. The head of the burner is 3 ¾ inches in diameter and the shaft runs 9 inches long. On the end where the hose is connected there is an adjustable air intake valve to modify the flame once the burner has been lit. We used a standard propane tank to run the burner throughout our engine tests. The burner is made to operate with a maximum capacity of 150,000 BTU/hr. We chose this burner for its higher power output, cost, and its size. This burner head was the closest in size compared to the heater cap.



Figure 26: Propane Burner (Left), Hose and Regulator Assembly (Right)

After purchasing the burner we tested its effectiveness. We assembled the line and connected the burner to the propane tank via the hosing seen above. Our initial test produced a

clear flame which was hard to distinguish. Holding the burner with an oven mitt, we boiled a pot of water above the flame. The burner produced a large amount of heat and the water rapidly boiled. In order to see the flame better and reduce hazards from holding the burner, we decided to secure the burner inside a grill for the next test. This time, the heat was consistent and the flame was visible, as seen in Figure 27. This test determined that the propane burner would be sufficient for our purposes because it is compact and capable of producing considerable energy.



Figure 27: Testing the propane burner by heating a pan of water to boiling

Generator

After testing the preliminary components of the Stirling engine, our generator was next to be tested. We had to make sure that it was going to be reliable and that it would produce a certain amount of power given a certain RPM input.

When looking at generators to achieve the electrical output from the mechanical rotation of the engine's shaft we searched for one that would not hinder the engine while it was trying to achieve full speed. We also needed this generator to be cost effective as we only had a little less

than \$200 to spend. We determined that the best solution to this problem would be to use a generator that is used on smaller wind turbines because when the wind is not blowing as hard then the force turning the shaft of the generator is also much less and the system should still be able to rotate freely. The solution to these problems came in the form of the Windzilla 12V DC Permanent Magnet Motor. The motor was roughly \$150 and could generate upwards of 250 Watts while having little to no resistance when trying to start the engine.

After receiving the generator, we used a drill to rotate the shaft while using multimeters to measure the voltage and amperage produced. We also had a tachometer pointed at the shaft of the generator so we could tell just how fast the shaft was spinning and correlate the values of amperage and voltage appropriately. The drill was spun at different intervals ranging from 700 RPM to 2300 RPM in order to test the minimum and maximum capabilities of the generator. The multimeters were set up such that the one measuring current was in series with the generator and the one measuring voltage was in parallel with a single resistor of varying resistance as shown in Figure 28.

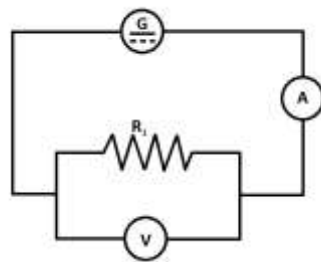


Figure 28: Wiring diagram used while testing the generator

Generator Experiments

1. The setup for our experiment consisted of aligning our power drill and generator by raising them with a small wooden 2x4 and one notebook, respectively. This allowed us to properly turn the generator without risking damage to the rotor inside the generator.



Figure 29: Preliminary testing setup

2. Next we positioned our tachometer a few inches away from the generator using a magnetic stand. This arrangement allowed for easier and more reliable data recording. We also applied a small strip of reflective tape on the spinning shaft of the generator, which allowed us to record revolutions per minute.
3. Following the tachometer, we set up one of the Extech multimeters to record the voltage being produced by the generator. We connected a T-splitter to the voltmeter that had a male BNC end and a BNC-to-alligator clip connector. Using this side we connected the black alligator clip to the black generator wire together with the resistor. The red alligator clip was then attached to the opposite side of the same resistor to properly record voltage over the resistor in parallel.
4. After the voltmeter was connected, we then connected our second Extech multimeter that would measure amperage across the circuit. To do this, we needed to connect this ammeter in

series. We connected the black lead of the ammeter to the end of the resistor (together with the voltmeter's negative connections as shown below in Figure 30). Then the red ammeter lead was connected to the bare red wire of the generator, completing the circuit. After connecting all required components, we could record results.

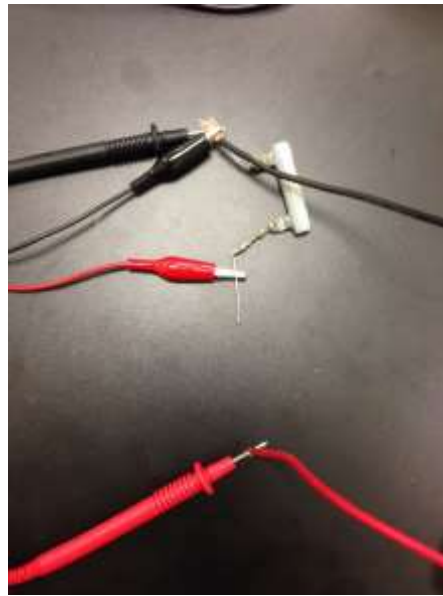


Figure 30: Series and Parallel wiring setup.

5. Before starting our tests, we made a video recording of the ammeter and voltmeter measurements. Since one person had to hold the drill and generator while the other person used the tachometer, it was difficult to also observe the multimeter values.

When recording the values we decided to use different resistors for R_1 to see if there was any change in the output. As can be seen by the graph in Figure 31 there was a significant difference in the power output. When looking further at the values for voltage we realized that those values did not change with respect to the different resistors plugged into the circuit. Using this knowledge along with Ohm's Law we can see that as the resistor value decreases, the current must increase to keep the same voltage. The generator could not run without having some sort of

resistance included in the circuit as we believe the power generated was going back into the generator and attempting to spin the shaft in the opposite direction of the drill, overloading the drill at only a few hundred RPM.

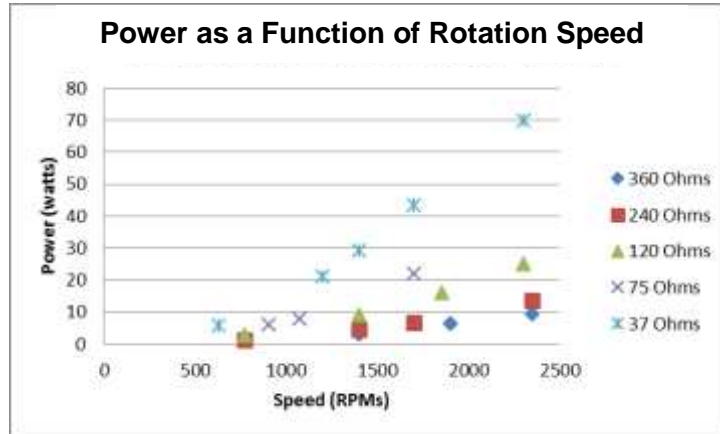


Figure 31: Graph showing the resulting power levels with different resistors

Engine Testing

Our Stirling engine was tested five times in order to assess the engine's performance, unsolved problems, and potential improvements, and to collect engine cycling temperature data. We will describe the required tools and components used for engine testing, the layout, and testing procedures here.

The components utilized for testing our Stirling engine were: propane burner, propane tank, DeWalt handheld drill, tachometer, National Instruments DAQ box, type K and type T thermocouples, VI files to measure temperatures, and a computer to record data.

While we intended to use a Fresnel lens as the heat source, during the engine testing we used a propane burner as a substitute. The burner is capable of providing an equivalent or even higher amount of energy than the lens, without the need for a bulky frame. The Fresnel lens was

also inadequate for the time period and location of the testing. As it relies on the sun, the short winter months did not allow us to focus an ideal amount of energy on the heater.

A handheld drill was used as a starter. In order to run the engine, there is not only a great amount of startup energy needed, but torque is also needed to overcome the static friction. The drill was able to rotate the crankshaft at approximately 1150 RPM at full speed.

Two type K thermocouples are secured near the hot piston and hot side of the regenerator to measure the temperature changes; two type T thermocouples are installed on the cooler side piston and cooler side of the regenerator as well. The propane burner was held with an oven mitt to allow for adjusting its orientation and distance from the engine.

The engine testing was conducted outdoors. The layout of engine testing can be seen from Figure 32 below, which shows how the propane tank and instrumentation equipment are separated from the engine's hot side. The procedure, described below, was created to ensure safety while also allowing us to have good data collection methods.

1. Prepare and arrange tools and components needed outdoors
2. Connect the propane tank and torch
3. Setup the instrumentation for temperature and RPM measurement
4. Fill the cooler with ice water
5. Start recording temperatures changes
6. Heat up the hot side of the engine
7. After several minutes, use the drill to turn the crankshaft and initiate the engine cycle
8. Record RPMs
9. Check engine running status



Figure 32: Testing the engine with the propane burner, drill, and DAQ box

4.0 Results and Discussion

Stirling Engine

Engine Test Mechanical Results

While we were able to gather good temperature data from our tests, we were not able to get the engine to run on its own. Repeated attempts to kick start the system, through pull-starting and by continuous rotation with the drill, always resulted in the engine quickly coming to a stop. As the numerical analysis will show, our dead volume was unacceptably high for the low-pressure working fluid. The testing of the engine revealed other significant design flaws, which we addressed.

The compressor lacked lubrication, so 5-50 wt. engine oil was added to the crankshaft chamber. Several dead volumes within the compressor were also discovered and filled with expanding foam and JB Weld. Various leaks in the heating and cooling sides of the engine were also observed as we rotated the crankshaft with the drill. Leaks on the cold side were easily fixed with Silicone gasket sealant, but the hot side proved impossible to fix. Any sealant we applied to the hot side would have quickly failed under the high temperature of the burner or Fresnel lens. When the engine was turned with a temperature difference applied, it was also observed that the RPM of the engine decreased. Further study of the pressures within the system would be required to determine the source of this issue.

Engine Temperature Results

To confirm that we were achieving the temperature differential necessary in order to run the Stirling engine, we used thermocouples to record the internal temperatures. By using a National Instruments Data Acquisition Box and a LabVIEW program, seen in Appendix C, we were able to record temperature data during testing. The results in Figure 33 show the increase of temperature as heat was applied over time. The highest temperature achieved inside the hot

piston was 423.8°C while the temperature inside the cooler piston was at 29.3°C, giving a temperature difference between the two pistons of 394.5°C. The fluctuations in the temperature around the 350 second mark are the result of readjusting the propane burner.

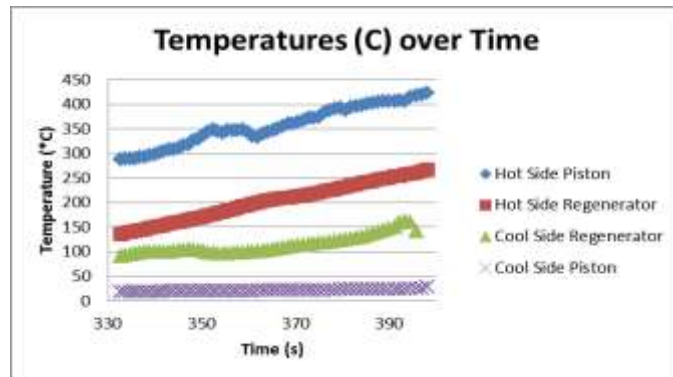


Figure 33: Temperatures recorded while the propane burner was used on the heater

Torque Measurements:

In order to determine the required power to turn the engine, first we needed to figure out the amount of torque required to turn the shaft. We performed this measurement by placing the piston at different locations of the cylinder (top, middle, and bottom) because different orientations of the cylinder had different required force. Then using a digital torque wrench we rotated the shaft to a complete cycle and measured the torque. The results of the measurements are shown in the table below.

Table 1 Torque Measurements

Piston Position	Torque (in-lb)	1 rev/sec
Top of cylinder	7.81	
Middle of cylinder then down	6.04	
Bottom of cylinder	10.47	
Middle of cylinder then up	7.17	
Average Torque	7.8725	0.889 Nm
Power (Watt)	5.58	
$P = T \cdot 2 \cdot (3.14) \cdot n$ (n= rev/sec)		



Figure 34: Torque wrench

Numerical Modeling and Analysis

Given relatively few known values, it is possible to fully describe the thermodynamics of a Stirling engine. Using well-established equations²⁴ for each part of the cycle, we have described the operation of our engine here. Table 2 shows the given engine data.

Table 2: Volumes, Temperatures, and other information inside the engine

Hot Piston Swept Volume (cm ³)	88.5	Phase angle (degrees)	90
Cold Piston Swept Volume (cm ³)	88.5	Heater Temperature (K)	696.94
Total Dead Volume (cm ³)	176.32	Cooler Temperature (K)	292.14
Regenerator Effectiveness (%)	64.85	Engine Frequency (RPM)	1150

Our engine used air at 1 atm (0.1013 MPa) as the working fluid. The total volume of air within the engine is 535.36 cm³, and the volume of each component is known. The engine is modeled as a true Stirling cycle, with dead volume and an imperfect regenerator.

Regenerator:

An ideal regenerator would absorb 100% of the incoming heat, and return it on the reverse cycle. Real regenerators operate at some level of effectiveness E , defined as:

$$E = \frac{T_L - T_C}{T_H - T_C}$$

Where T_L is the temperature of the gas leaving the regenerator from cold to hot, T_C is the temperature of the gas in the cooler, and T_H is the temperature of the gas in the heater. Given our temperature data:

$$E = 100 * \left(\frac{554.64 - 292.14}{696.94 - 292.14} \right) = 64.85\%$$

²⁴ 'Stirling Engine Design Manual, 2nd Edition'. Jan 1, 1983. Martini Engineering, NASA Technical Reports Server.

Due to its non-ideal nature, the regenerator should operate at an effective temperature to maximize its effectiveness. This temperature can be approximated as the arithmetic mean of the cold and hot piston temperatures:

$$T_R = \frac{T_H + T_C}{2} = \frac{696.94 + 292.14}{2} = 494.54 \text{ K}$$

This is consistent with the temperatures recorded within the regenerator during operation.

This temperature is used to calculate the amount of functional working fluid within the engine:

$$M = \frac{P}{R} \left(\frac{V_H}{T_H} + \frac{V_R}{T_R} \right) = \frac{0.1013}{8.314} \left(\frac{88.5}{696.94} + \frac{77.18}{494.54} \right) = 0.0035 \text{ mol}$$

Compression:

The engine compresses from 143.56 cm³ to 55.06 cm³, on both the hot and cold sides.

The non-ideal compression equation for a point x in the compression stroke is:

$$P(x) = \frac{M * R}{\frac{V_C(x)}{T_C} + \frac{V_R}{T_R}} = \frac{0.0035 * 8.314}{\frac{V_C(x)}{292.14} + \frac{77.18}{494.54}}$$

$$P(x) = \frac{8.50}{V_C(x) + 45.59}$$

Integrating with respect to the maximum and minimum volume gives the work of compression per cycle:

$$W(1) = \int_{55.06}^{143.56} \frac{8.50}{V_C(x) + 45.59} dV(x)$$

$$W(1) = 8.5 \ln \left(\frac{55.06 + 45.59}{143.56 + 45.59} \right) = -5.36 \text{ Joules}$$

Note that the value is negative because it is being supplied to the system.

Expansion:

The equations for expansion are analogous to compression, and it is here that the useful work is produced.

$$P(x) = \frac{M * R}{\frac{V_H(x)}{T_H} + \frac{V_R}{T_R}} = \frac{0.0035 * 8.314}{\frac{V_H(x)}{696.94} + \frac{77.18}{494.54}} = \frac{20.28}{V_H(x) + 108.77}$$

Integrating to find the work done by the expansion per cycle:

$$W(3) = \int_{55.06}^{143.56} \frac{20.28}{V_H(x) + 108.77} dV(x)$$

$$W(3) = 20.28 \ln\left(\frac{143.56 + 108.77}{55.06 + 108.77}\right) = \mathbf{8.76 \text{ Joules}}$$

Net work efficiency, and power:

$$W = W(3) + W(1) = 8.76 - 5.36 = \mathbf{3.4 \text{ Joules}}$$

$$\eta = \frac{W(3) + W(1)}{W(3)} = \frac{3.4}{8.76} = \mathbf{39.53\%}$$

For the measured temperature differential, the engine produces 3.4 Joules per cycle. One cycle of the pistons is equal to $2 (\# \text{ pistons}) * 0.066m (\text{travel distance}) = 0.132 m$

At 1150 RPM, the speed is $\frac{1150 * 0.132}{60} = \frac{2.53m}{s}$ and the time per cycle is $\frac{0.132}{2.53} = 0.052s$

Therefore the power produced per cycle at 1150 RPM is:

$$\frac{3.4 \frac{J}{\text{cycle}}}{0.052 \frac{s}{\text{cycle}}} = \mathbf{65.2 \text{ W}}$$

The power required by the engine, given the average torque for continuous rotation, is:

$$P = \tau * \omega = 0.889 * \left(\frac{2\pi}{0.052}\right) = \mathbf{107.42 \text{ W}}$$

The power to move the engine is greater than the power produced by the cycle at the established temperature difference. This explains why the engine does not run under our observed conditions. Assuming the power required by the engine, dead volume, and pressure values remain the same, the engine will not eclipse the power requirement threshold below a temperature difference of 1227 K, or 953.85 C. See Figure 35 for details.

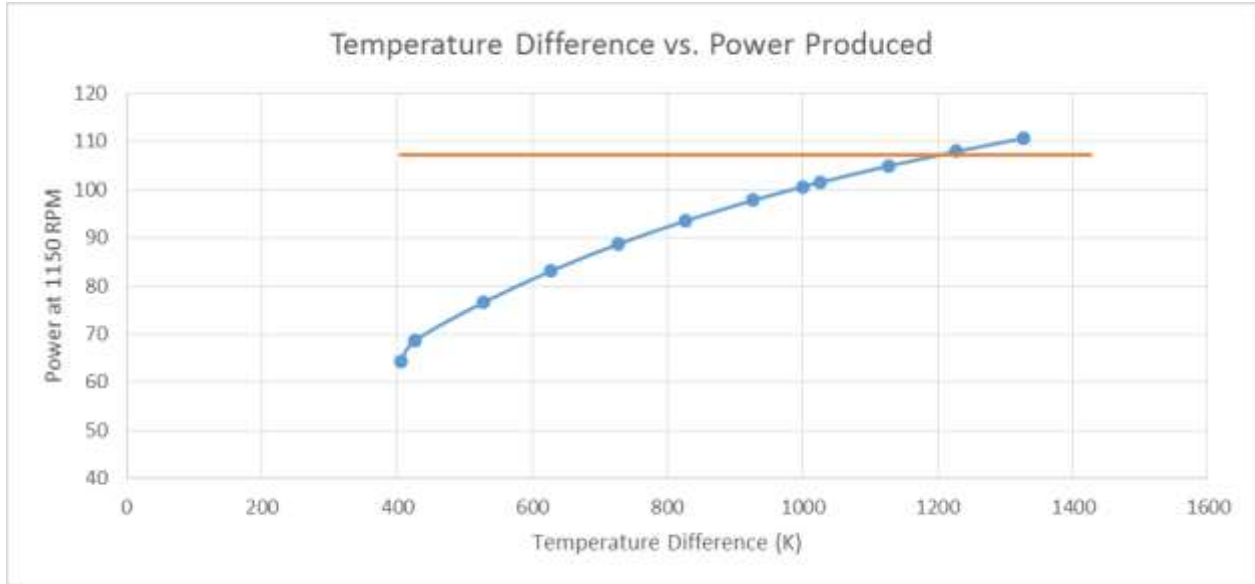


Figure 35: Power produced as a function of temperature differential

As the graph above shows, any differential above approximately 1200 K would be enough for the engine to run in its current configuration. The temperature differential is not the only independent variable however. Dead volume and pressure can also be changed to improve the power output of the engine. It may be desirable to change those variables first to avoid unnecessarily high temperature requirements.

Solar concentrations in different locations

As discussed earlier, we used the Fresnel lens as a means of concentrating the power of the sun into a small area. In order to determine the potential of the lens we had to first find out how much energy the earth receives from the sun. This data varies significantly based upon a variety of factors including geographic location and time of year. “The National Renewable Energy Laboratory (NREL) is the U.S. Department of Energy's primary national laboratory for renewable energy and energy efficiency research and development”.²⁵ The NREL collects data on the amount of sun light which reaches earth across the country. This data is collected and compiled by month with the monthly maximum, minimum, and average irradiance received. Using their solar prospector tool we were able to determine the average amount of energy received in Worcester during the month of November, when we ran our experiment. With data updated in 2009, we were able to find areas of the country which would be best suited for the technology we are developing. We found that in the area of Death Valley, California there is more than an average of 11kWh/m²/day during the month of June while the average for Worcester in November is 2.64kWh/m²/day.²⁶ Using the data obtained we were able to find an average ratio of 4.23 between Death Valley in June to Worcester in November. During our experiments we were able to obtain a maximum of 263 watts over a 45 second period of the test. With our efficiency calculations, we saw that this number could be as high as 457W. Given this ratio, in Death Valley our set up could receive more than 1900 watts on a consistent basis in June. Also, we could receive 1700 watts on a consistent basis during the months of May through September along with more than 1100 watts on a consistent basis during the entire year.

²⁵ "Overview." NREL.gov. NREL, 8 Nov. 2013. Web. 10 Dec. 2013.

²⁶ "The Solar Prospector." Solar Prospector. NREL, Sept. 2012. Web. 2 Dec. 2013.

Table 3: NREL data from Worcester and Death Valley, measured in Wh/m²/day.

Wh/m ² /day	Worcester			Death Valley (36.06, -117.67)		
	Max	Avg	Min	Max	Avg	Min
January	4584.19	3385.94	2529.26	7652.81	6837.56	5095.77
February	4550.93	3673.69	2920.89	8760.43	7000.51	4760.14
March	4727.94	4122.49	3018.13	9892.74	8758.52	7300.06
April	5289.27	4310.55	2729.87	9789.13	8596.02	6637.67
May	5203.77	4055.51	2756.26	11208.48	10175.8	9120.29
June	5002.9	4088.55	2358.8	11856.33	11183.25	9397.23
July	5396.58	4568.93	3902.97	11541.29	10559.07	9689.94
August	4921.87	4309.98	3733.13	10768.39	10186.97	9405.77
September	5286.3	4249.71	3546.2	10246.27	9856.02	9094.27
October	4099.32	3375.06	2358.29	9433.16	8455.08	7394.58
November	3119.7	2641.21	2238.43	8286.23	7546.38	6053.73
December	3727.77	2893.59	2458.03	7950.77	6600.53	5719.45

Table 4: Ratio of Death Valley in June vs Worcester in November.

Max	3.800
Avg	4.234
Min	4.198

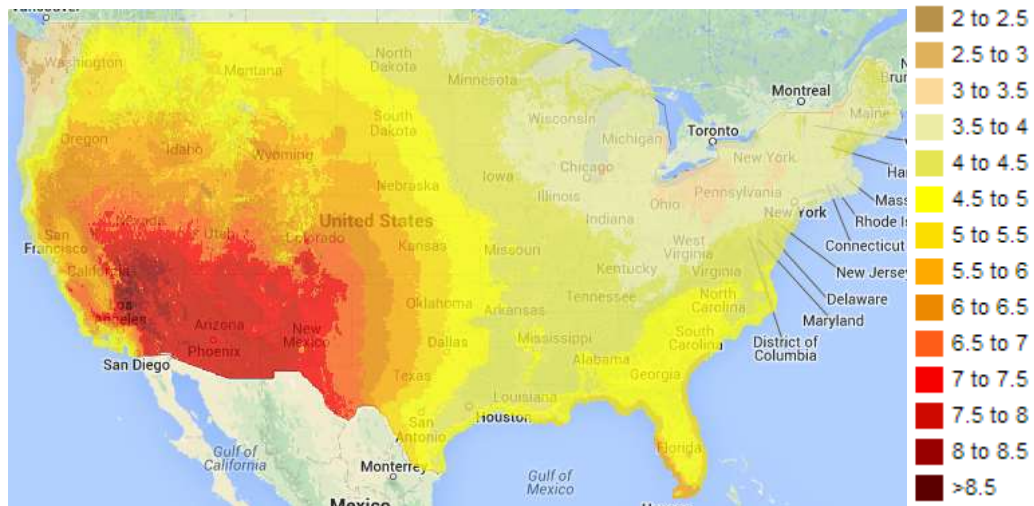


Figure 36: Map of average annual solar irradiance for the United States. Scale with units of kWh/m²/day.

With the information from NREL, we can find areas in the United States which would be suitable for developing this technology. Anywhere that receives 6 or more kWh/m²/day would be

able to produce an average of more than 1000W throughout the year. This area ranges from Northern California in the west, to a majority of Colorado in the east. It also ranges from southern Oregon, Idaho, and Wyoming in the north all the way to the Mexican border in the south. While our system may not be well suited for Worcester, it shows good promise in many other parts of the country.

Lens Optimizations

As discussed above, we were only able to see peaks of a few hundred watts produced by the lens and these results were over relatively small time intervals. Due to this fact we sought to determine how much power we could produce based on different lens sizes. These calculations are based on a lens which converts 100% of the energy received. The Fresnel Lens we acquired is 0.76 square meters. In order to produce 1000W of power with this lens it would require more than double the annual average solar energy received anywhere in the country. Using the raw data from the NREL we found out that our lens has the potential to produce an average of only 125W during November which happens to be the month which receives the least amount of solar energy. To produce 1000W – as a way of accounting for losses throughout the system – with a lens similar to ours, also in November, the lens would need to be nearly six square meters. This is equivalent to an 8 foot by 8 foot lens area or 8 lens which match our size.

Fresnel Lens

To test the Fresnel lens, we concentrated solar rays onto a glass jar, which was spray-painted black in order to maximize thermal insulation. The jar contained 6 fl. oz. of water that was at a known temperature. A type K thermocouple was placed inside the jar in order to measure the change in temperature of the water. We conducted four tests for which the results will be discussed below. We took temperature measurements every 15 seconds and from the data collected we calculated the power outputs from different time intervals. Our best results were seen during the third and fourth tests where we were able to consistently obtain more than 117W of power and peaks at 263W. The table below shows the summary of the four experiments we conducted.

Table 5: Summary of experimental data

	Power Output		
	Overall Average	15s Peak	60s Peak
Test 1	37.94W	57.61W	33.60W
Test 2	72.46W	71.32W	51.44W
Test 3	117.86W	123.45W	116.59W
Test 4	102.47W	246.89W	220.37W

Lens Experiments

After running our experiments we used a variety of equations to analyze the data we obtained. Each of these equations and their applications will be discussed in further detail below.

$$Q = mc\Delta T$$

The equation above was used in order to determine the amount of energy that was absorbed by the water during heating.²⁷

Q = amount of energy, measured in joules

m = mass of water, 176.94 grams

c = specific heat capacity of water, 4.186J/gram·°C

ΔT = change in temperature, measured in °C

²⁷ "Specific Heat." *Specific Heat*. N.p., n.d. Web. 5 Dec. 2013. <<http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/spht.html>>.

$$Q = hA(T_s - T_\infty)$$

The equation above was used to find the heat loss due to convection.²⁸

Q = energy lost, measured in joules
h = heat transfer coefficient, 15W/m²·K
A = area at the top of the jar, 0.002827m²
T_s = water temperature, measured in K
T_∞ = ambient temperature, 288.71K

$$Q = \frac{2\pi kL \cdot (T_s - T_\infty)}{\ln \frac{r_o}{r_i}}$$

The equation above was used to find the heat loss due to conduction.²⁹

Q = energy lost, measured in joules
k = thermal conductivity of glass jar, 1.3W/m·K
L = length of the jar, 0.097m
T_s = water temperature, 317.539K
T_∞ = temperature of the jar, 308.71K
r_o = outer radius of the jar, 0.0685m
r_i = inner radius of the jar, 0.06m

Experimental Error

It should be noted that throughout each of our tests we saw many types of error. Firstly, since we do not know how our lens was constructed we do not know the real efficiency. Also, we saw great heat losses through both convection and conduction, since we conducted the experiments in a windy, 35°F environment. We also believe that the angle of the lens as well as the focal area reaching the jar played a part in energy losses since we needed to move and adjust the lens a few times based on the sun's location. As well, it should be noted that missing data

²⁸ Elert, Glenn. "Convection." - *The Physics Hypertextbook*. N.p., n.d. Web. 5 Dec. 2013.

<<http://physics.info/convection/>>.

²⁹ "Heat Conduction." N.p.: n.p., 2007. 12. Web. 5 Dec. 2013.

<<http://v5.books.elsevier.com/bookscat/samples/9780123735881/9780123735881.pdf>>.

points in each of the graphs below represent times where a data point was missed due to lack of a reading, which occurred when the thermocouple was disconnected to the display unit. Finally, the thermocouple is known to have a maximum error of about 36°F.³⁰

Test 1

The first test we ran for this experiment was successful. We collected good data and found room for improvements. The initial temperature of the water was 73.2°F and lasted for three minutes and 45 seconds. The temperature of the water increased to 87.8°F.

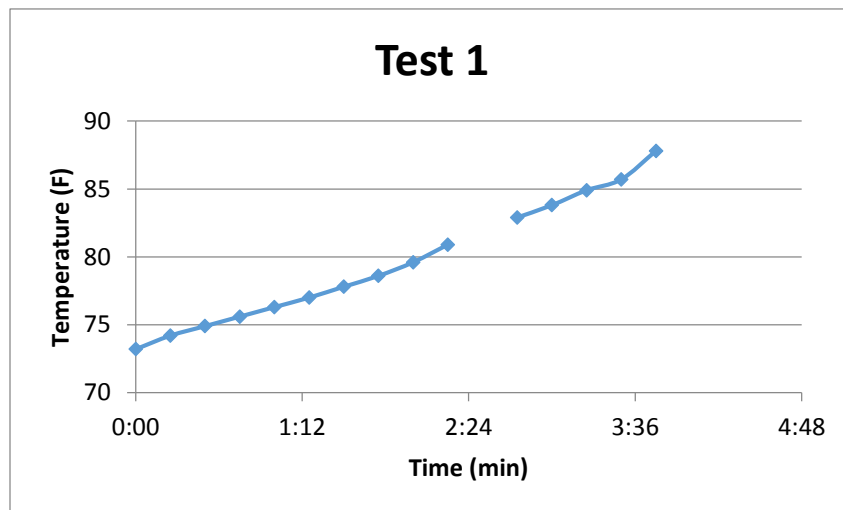


Figure 37: Temperature change during Test 1

During this test we averaged 38 watts over a three and a half minute period with a peak 15 second interval of 57 watts. This test showed good consistency and we were able to use it to improve future tests. The graph below shows the average power in the experiment.

³⁰ "Introduction to Thermocouples." *Omega Engineering*. N.p., 2013. Web. 16 Dec. 2013.

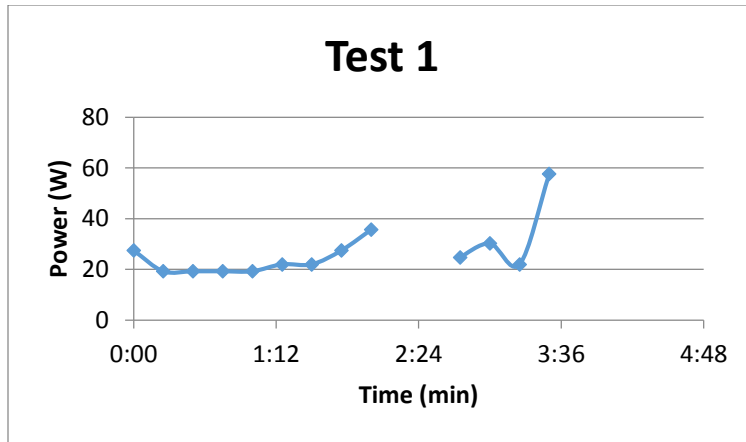


Figure 38: Power received throughout the first test.

Test 2

In the second experiment we started with an initial temperature of water at 88.3°F and lasted over 11 minutes. During the test we were able to increase the temperature of the water to 151.4°F. We averaged an increase of 5.5°F per minute during this test, which was an improvement upon the 3.9 degree average on the first test. The graph below shows the results of the experiment.

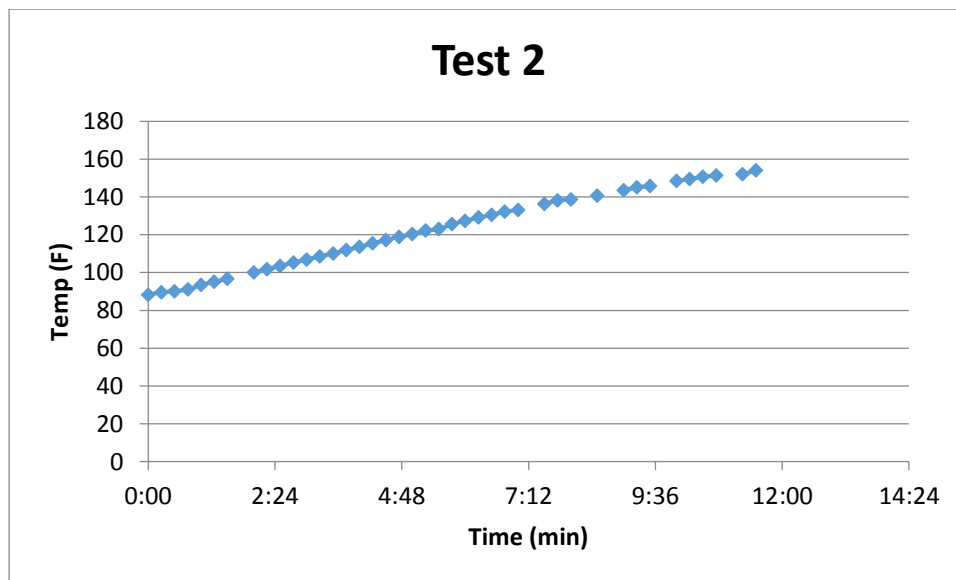


Figure 39: Temperature change during Test 2

Test 2 had some relatively consistent data throughout the experiment. Over the first 6 and a half minutes we saw an average of 80 watts of power output with peaks of 71 and 63 watts over a 15 second period, while each minute between 1:00 and 7:00 was between 45 and 47 watts for the individual 60 second periods. The data was consistent for the first half of the test, but trailed off later on, which we feel is attributed to the orientation of the sun as it moved during the experiment and how we needed to adjust the lens in the direction of the sun as well as the presence of some clouds. The graph below shows the power output during the experiment.

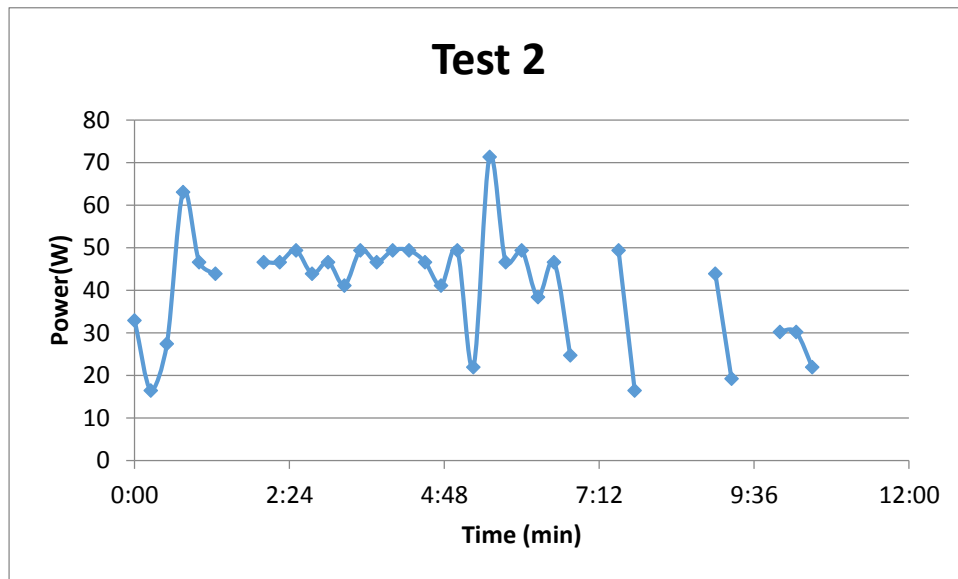


Figure 40: Power received throughout the second test.

At the end of the second test we noticed that the water in the top of the jar appeared to be boiling, though the thermocouple recorded only 150°F at its depth. The thermocouple was moved higher in the water and we noticed a spike in temperature over 200°F. Due to this occurrence, we conducted another test where the thermocouple was placed higher in the jar. As it can be seen from the data obtained in test 3, this modification allowed us to obtain higher temperatures and energy outputs.

Test 3

For the third test we started with water at 66.6°F and raised it to 176.4°F over a time of eleven and a half minutes. This gives us an average increase of 9.6 degrees per minute which was another great improvement from previous tests. It can also be seen that our data was again consistent.

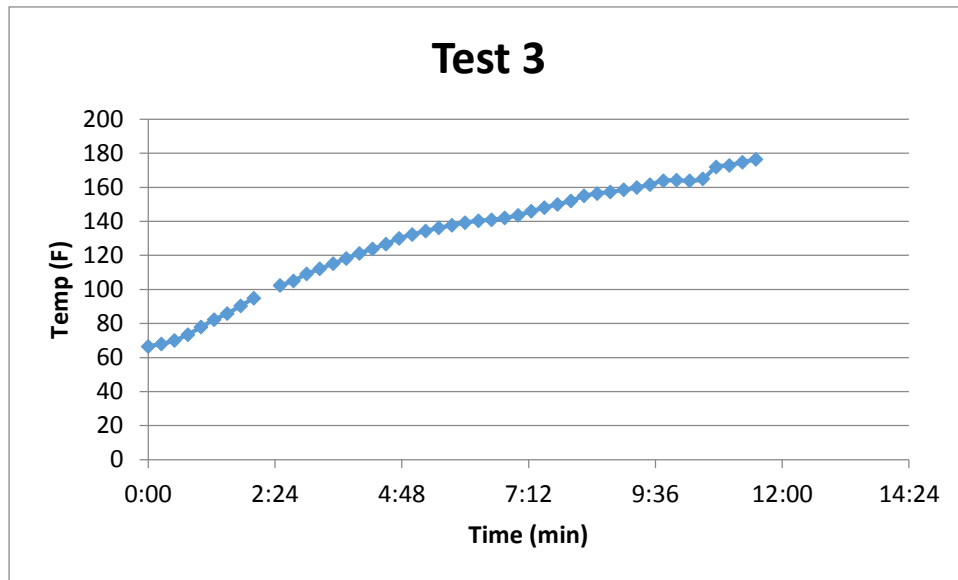


Figure 41: Temperature change during Test 3

Test 3 provided some good insight into our data collection methods while also helping us realize some sources of error. Throughout this test we saw an average of almost 118 watts of power production with peaks of 123 watts for 15 second intervals as well as 116 watts for 60 second intervals.

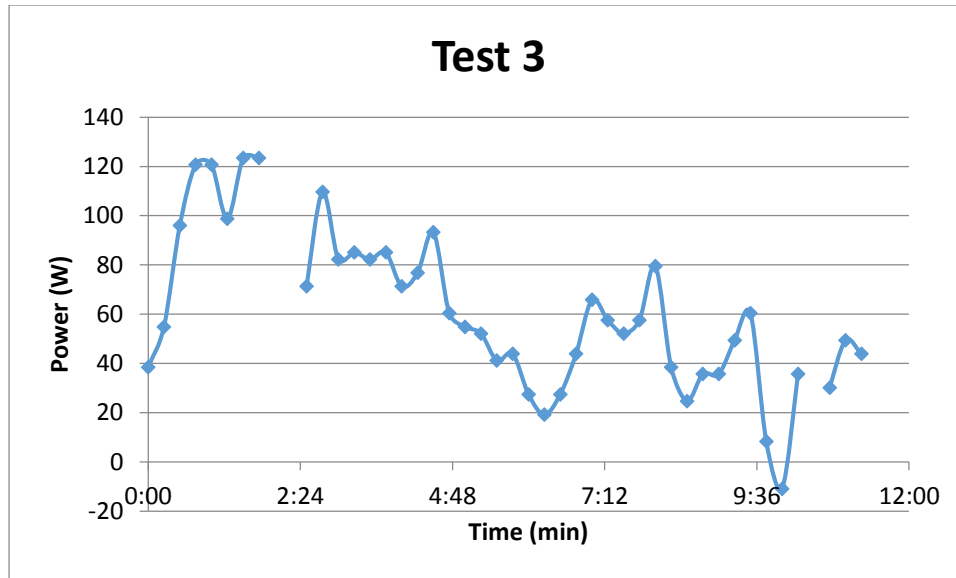


Figure 42: Power received throughout the third test.

As it can be seen from Figure 42, the power generated dissipates over time. This can be attributed to the movement of the sun as well as the possibility of wind slightly altering the direction of the frame. Additionally, the rise in water temperature leads to a great heat loss to the external environment.

Test 4

For our fourth and final test we began with water at 105.6°F and raised it to 182°F for an average increase of 10.9 degrees per minute. Another steady improvement, this test also brought us our highest peak average of 263 watts over a 45 second time period. This test brought about some consistent numbers.

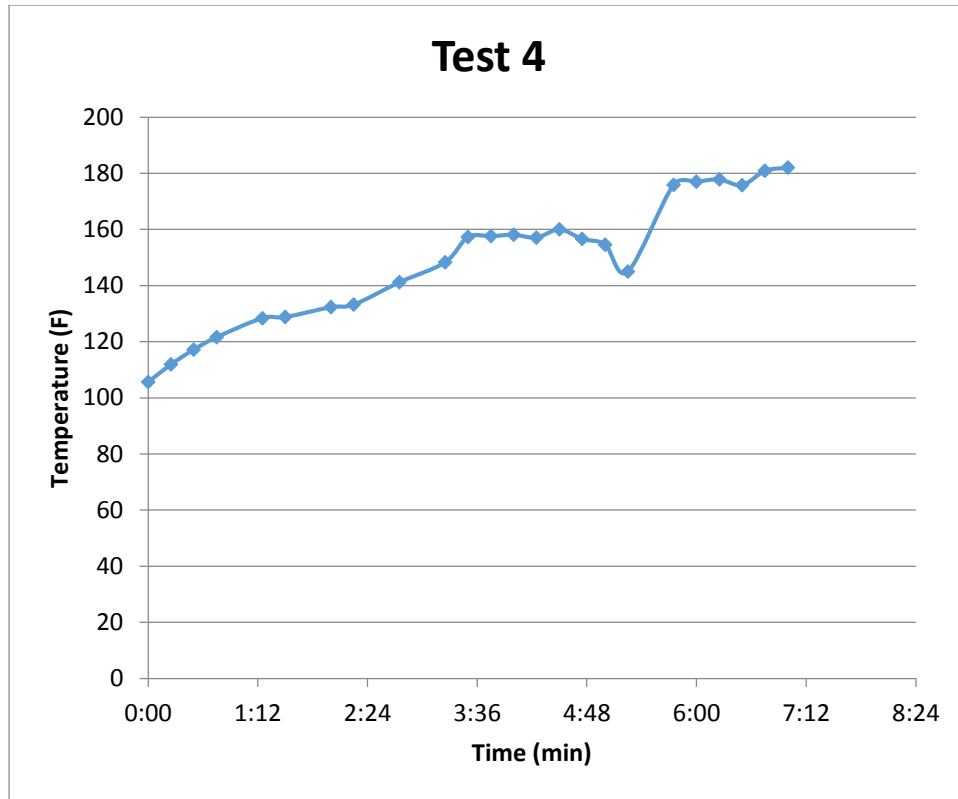


Figure 43: Temperature change during Test 4

In this test we also saw an average of 74.84W. There were some spots of data which had less consistency here which is the reason for some missing areas on the power graph. For this experiment we were also able to calculate heat losses through convection and conduction which allowed us to gauge an approximate efficiency of our system.

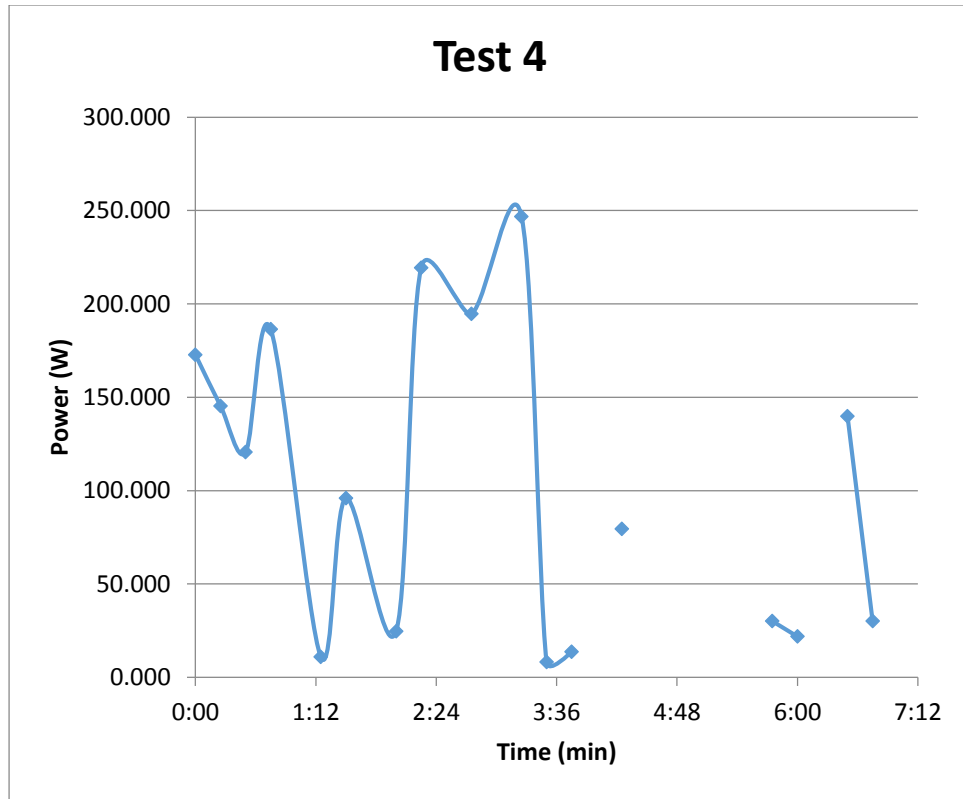


Figure 44: Power received throughout the fourth test.

Convection Loss

Within this experiment we were met with some losses. One of the first heat losses was due to convection. The top of the jar was not closed, allowing heat to escape into the atmosphere. In order to calculate the amount of heat lost to convection we used equation 2.

$$Q = hA(T_s - T_\infty)$$

After calculating the heat loss every 15 seconds, we were able to determine an average loss of 2.104W throughout the experiment.

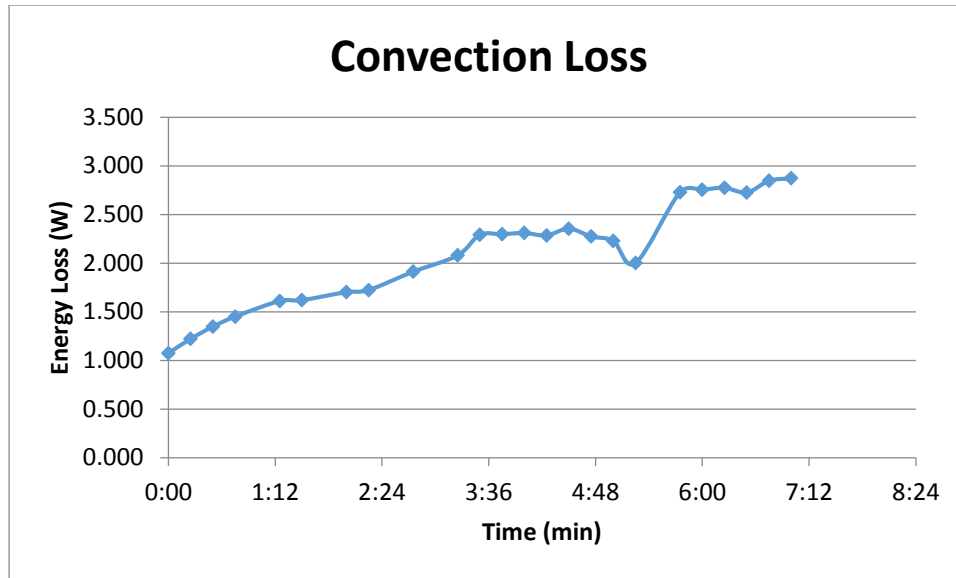


Figure 45: The graph above shows that as the temperature of the water increased, there were larger losses due to convection.

Conduction Loss

Another loss we experienced was through conduction. In order to determine the energy loss through conduction we used equation 3.

$$Q = \frac{2\pi kL \cdot (T_s - T_\infty)}{\ln \frac{r_o}{r_i}}$$

To calculate the heat loss through conduction, we had to assume the temperature of the glass increased linearly with time. Therefore we can use the initial heat loss as the average for this test. By using this process we were able to determine an average loss of 52.994W throughout the experiment. Due to these losses, we sought to determine how many energy was absorbed by the system.

Energy Absorbed

We calculated the average energy absorbed by the water and that lost to the surroundings to determine our systems efficiency therefore allowing us to calculate the systems potential. We determined the energy absorbed to raise the water temperature by using equation 1.

$$Q = mc\Delta T$$

Based on this equation we were able to determine the average heat absorbed by the water was 74.8448W. By combining the amount of power absorbed and lost we can say that the system contained an average of 129.943W. Since only a portion of this actually gets absorbed, we can use this information to determine the efficiency of our system. By dividing 74.8448 by 129.943, we come to the conclusion that only 57.6% of the energy goes into heating the water. This means that the system has the potential to be 1.74 times more efficient. Using this efficiency we can say that based on our 45 second peak of 263W, we could obtain up to 457W during peak times. We will use this data in our numerical analysis to show the systems potential capacity during different times of the year in different parts of the country.

Generator

In our electrical generator experiments, we used a power drill as our testing power source. At first we tested our generator using athletic tape and a pair of nails, hoping that the torque created would not overcome the connection. Unfortunately, these attempts did not give us qualitative results since there was slippage in the connection and the torque from the drill was not transferring correctly. After a few trips to the local hardware shop, we were able to securely attach our power drill to our generator by using a socket adapter that was able to fit the spindle nut without any loss of power.

Generator Results

After recording data for multiple tests of the generator, we created the graph shown in Figure 46. The graph shows the current recorded through each of the resistors that we used. Each of the trend lines can be used to show the pattern that occurs with the current as the resistance through the system is decreased. Combining this pattern with the knowledge that our system will

provide some resistance, indicates that this will yield large amounts of amperage. When looking at the graph one can see that our highest amperage recorded was with the 37 ohm resistor at a speed of roughly 2300 RPMs. Comparing the values for the 37 ohm resistor to that of 75 ohm resistor, we observe the slope of the line to be twice as much for half the resistance. We can then estimate that a system with ~20 ohms of resistance will peak at 2.7 amps.

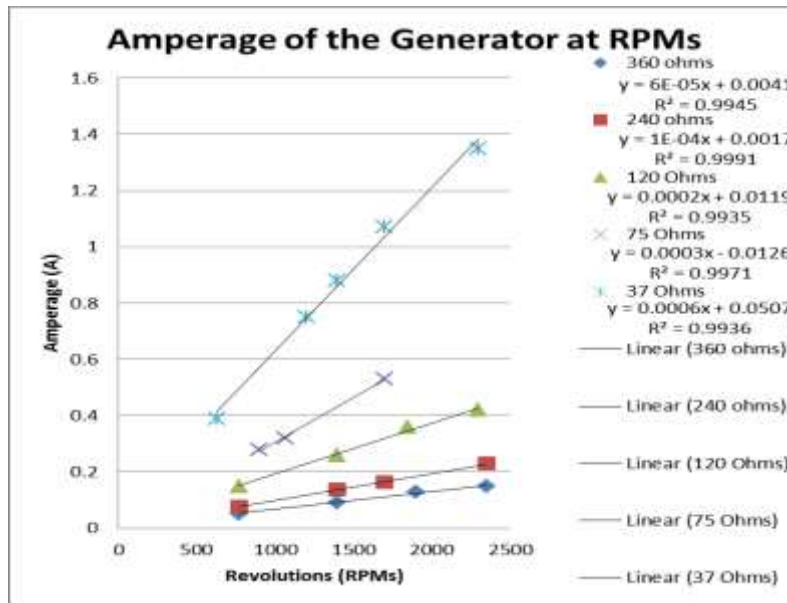


Figure 46: A graph showing the results and lines of best fits for different resistors and amperage

We also recorded data on the voltage drop across the resistor and found that the voltage did not differ at all when the resistance was either increased or decreased. The relation between voltage and speed is also linear which can be seen in Figure 47, which shows the recorded values for four different speeds from 700 to 2300 RPMs. Since the relation is linear, we can use the equation shown in Figure 47 to estimate a rough voltage from the speeds we will be getting with the Stirling engine attached.

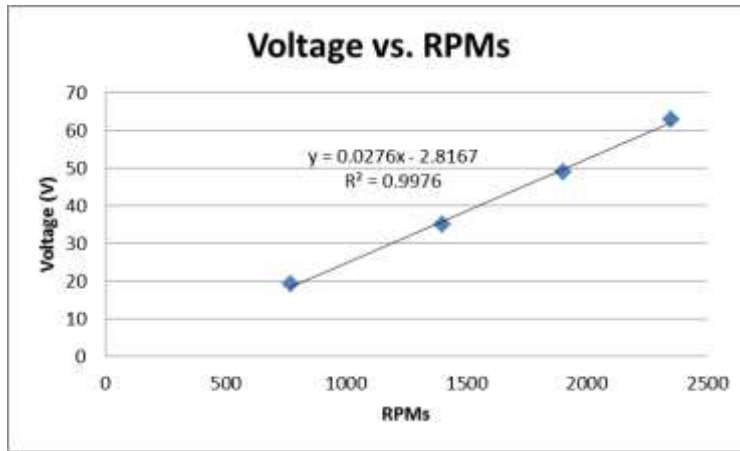


Figure 47: A graph showing the voltage recorded for different speeds

With these two charts of data we are able to look at the power curves of the generator using the equation $P=IV$. Using this equation, we end up with the distribution of Figure 48 below. Since both the current and voltage are linear with respect to the speed of the generator, it is fitting that the power curves end up as quadratic functions. Figure 48 also reinforces the fact that in order to get the most out of this generator we want to focus on increasing the speed of the turning shaft. By also decreasing the resistance in the circuit, we can increase the current and generate more power.

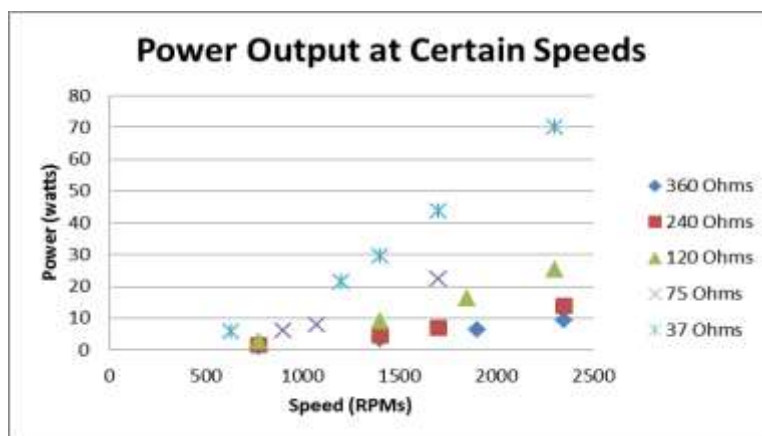


Figure 48: A graph showing the power output at certain speeds for the different resistors tested

5.0 Conclusions

Throughout the process of designing, manufacturing, and testing our Stirling engine, we have uncovered many new insights, problems and solutions concerning the different portions of the engine. We applied our knowledge of thermodynamics to the design of the engine, and developed formulas to predict its power output at different temperature differentials. Overcoming many engineering and design challenges, we were able to build the engine and include the tools necessary to record data inside the engine.

From the numerical analysis, we found that our engine is achieving a power output of only 65.2 Watts. This was not large enough to keep the engine in motion after applying an initial pull start. Changes necessary to increase the work output of the engine would include pressurizing the system, as the value for the pressure inside the system has a linear correlation to the work output. Increasing the pressure inside the system would allow the gasses inside to exhibit incompressible flow, and improve mass transfer between the hot and cold sides of the engine. If the machine is pressurized however, there is a risk of explosive decompression, and a pressure gauge becomes necessary to monitor the system. Another route to pursue in order to improve the engine is to reduce the dead volume. The calculated dead volume inside the system of 176.32 cm^3 can be decreased by changing the size and shapes of the pipes, heater and cooler. The shape of the heater currently works but is not ideal for the flow of the gasses from inside the hot piston to the piping connecting to the cool side of the engine.

Due to the restraints on our resources and prioritizing the design and manufacturing of the necessary cooler and heater sections, the process of developing the compressor to an optimum state was rather neglected. The compressor could be improved by replacing or rebuilding portions of the engine to better suit the needs of a Stirling engine. The phase angle of the pistons would need to be shifted to better optimize the cooling and heating that occur in each

piston chamber. The considerable friction occurring inside the compressor could be addressed through the bearings and bushings along the crankshaft. Although our design was not able to sustain the work conversion from the heat of the burner to the mechanical rotation of the crankshaft, we were able to build an engine and maintain a temperature differential inside the system.

Opportunities for Future Improvement

Several problems remain to be addressed within the engine. First among them is the overall lack of useful work output by the engine. Most of the work is being absorbed by the friction of the crankshaft and piston linkages, and possibly by inferior bearings. Further inspection of the compressor block is recommended to isolate and rectify these problems.

As mentioned in the methodology, a serious risk of engine damage was mitigated by abandoning the mesh type regenerator in favor of a foil-type. However, it is the opinion of the team that a mesh regenerator without the fragility of steel wool would be more efficient, and have less dead volume, than our current system. Dead volume can also be reduced by decreasing the diameter of the connecting pipe between the caps. Given the relatively low swept volume of the pistons, it is likely that this excess pipe volume is significantly reducing the mass transfer rate of hot and cold working fluid.

The lack of pressurization may also be an opportunity to improve the engine. Most successful Stirling engines in our research were pressurized to some extent. Currently there are leakage issues on the hot side preventing pressurization, and more may become apparent as pressure is increased. The added pressure may also pose a safety hazard. Good fit tolerances will be required when implementing pressurization. A means for measuring the pressure should also be implemented, taking measures to avoid exposure to high temperatures.

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Appendix A: Generator Testing Setup

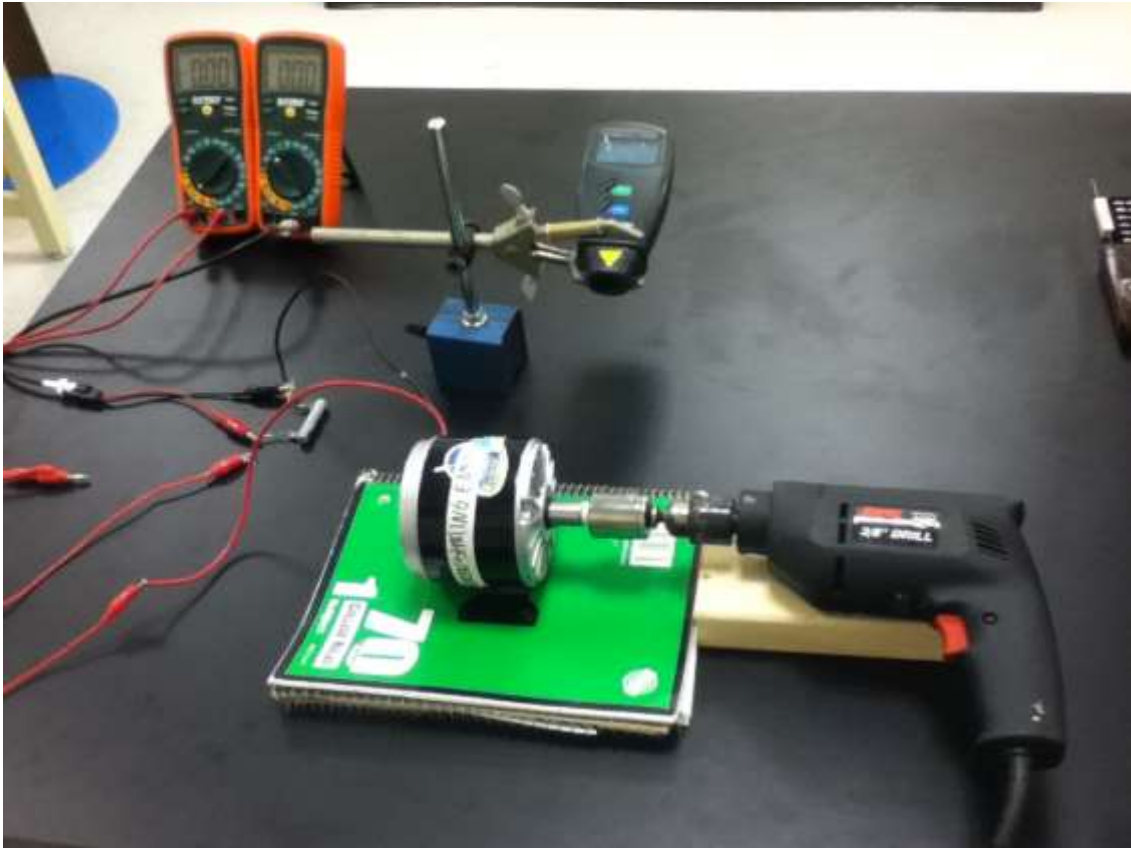


Figure 49: Image of the set up used for the testing of the generator

Appendix B: Fresnel Lens Test Data

Table 6: Experimental data Details and Calculated losses from Test 4.

Time	Temp (°F)	Temp (°C)	Temp (K)	Delta T	Q (J)	Power (W)	Q loss Conduction (W)	Q loss Convection (W)
0:00	105.6	40.88889	313.8889	3.5	2592.348	172.823		1.074
0:15	111.9	44.38889	317.3889	2.944444	2180.864	145.391	52.994	1.222
0:30	117.2	47.33333	320.3333	2.444444	1810.529	120.702	70.668	1.347
0:45	121.6	49.77778	322.7778	3.777778	2798.09	186.539	85.340	1.450
1:15	128.4	53.55556	326.5556	0.222222	164.5935	10.973	108.016	1.611
1:30	128.8	53.77778	326.7778	1.944444	1440.193	96.013	109.349	1.620
2:00	132.3	55.72222	328.7222	0.5	370.3354	24.689	121.021	1.702
2:15	133.2	56.22222	329.2222	4.444444	3291.87	219.458	124.022	1.724
2:45	141.2	60.66667	333.6667	3.944444	2921.535	194.769	150.699	1.912
3:15	148.3	64.61111	337.6111	5	3703.354	246.890	174.375	2.079
3:30	157.3	69.61111	342.6111	0.166667	123.4451	8.230	204.387	2.291
3:45	157.6	69.77778	342.7778	0.277778	205.7419	13.716	205.387	2.298
4:00	158.1	70.05556	343.0556	-0.55556	-411.484	-27.432	207.054	2.310
4:15	157.1	69.5	342.5	1.611111	1193.303	79.554	203.720	2.287
4:30	160	71.11111	344.1111	-1.88889	-1399.04	-93.270	213.390	2.355
4:45	156.6	69.22222	342.2222	-1.11111	-822.968	-54.865	202.052	2.275
5:00	154.6	68.11111	341.1111	-5.33333	-3950.24	-263.350	195.383	2.228
5:15	145	62.77778	335.7778	17.16667	12714.85	847.657	163.371	2.002
5:45	175.9	79.94444	352.9444	0.611111	452.6322	30.175	266.411	2.729
6:00	177	80.55556	353.5556	0.444444	329.187	21.946	270.079	2.755
6:15	177.8	81	354	-1.11111	-822.968	-54.865	272.747	2.774
6:30	175.8	79.88889	352.8889	2.833333	2098.567	139.904	266.078	2.727
6:45	180.9	82.72222	355.7222	0.611111	452.6322	30.175	283.084	2.847
7:00	182	83.33333	356.3333	-83.3333	-61722.6		286.752	2.873

Appendix C: LabVIEW VI

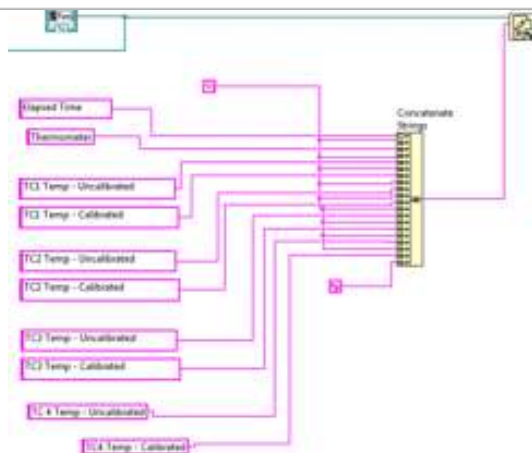
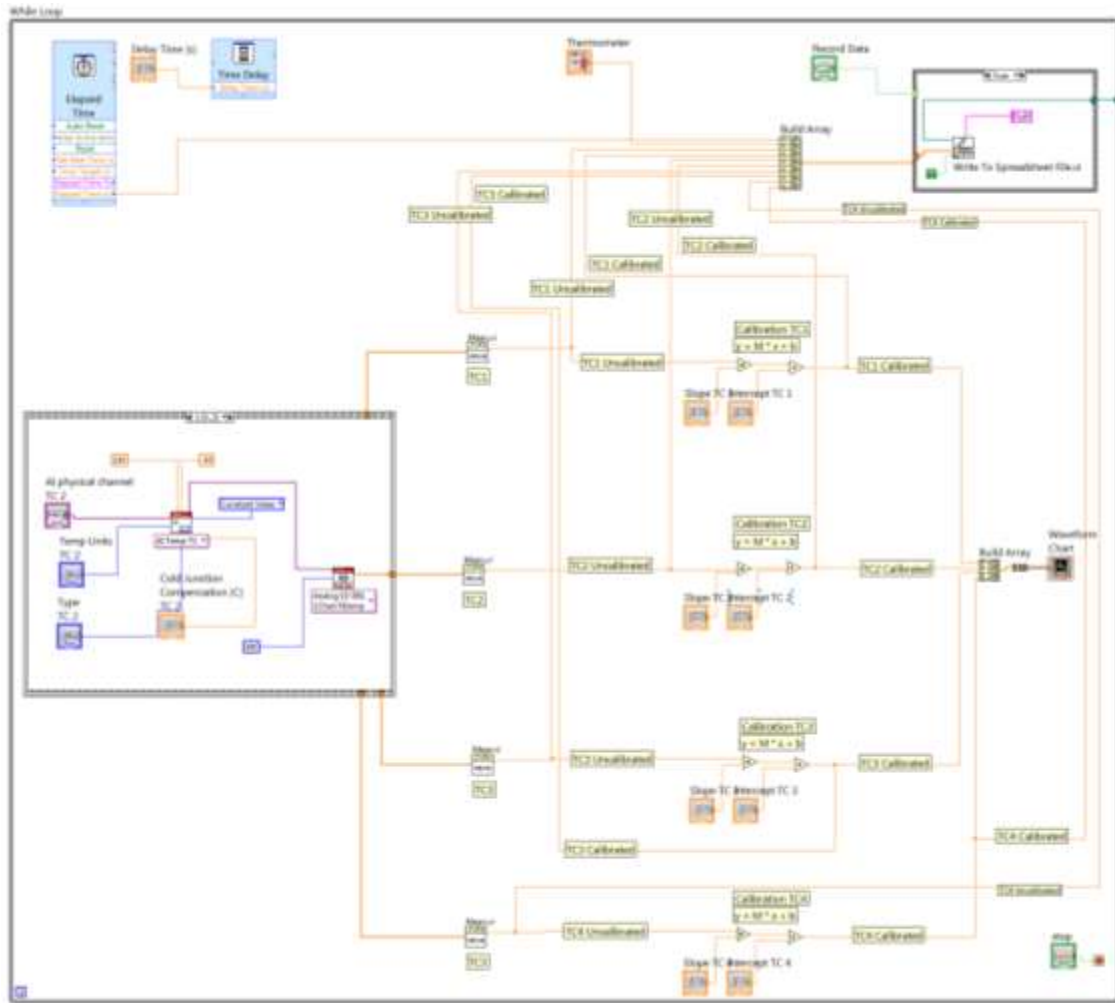


Figure 50: Block Diagram of the written LabVIEW Program

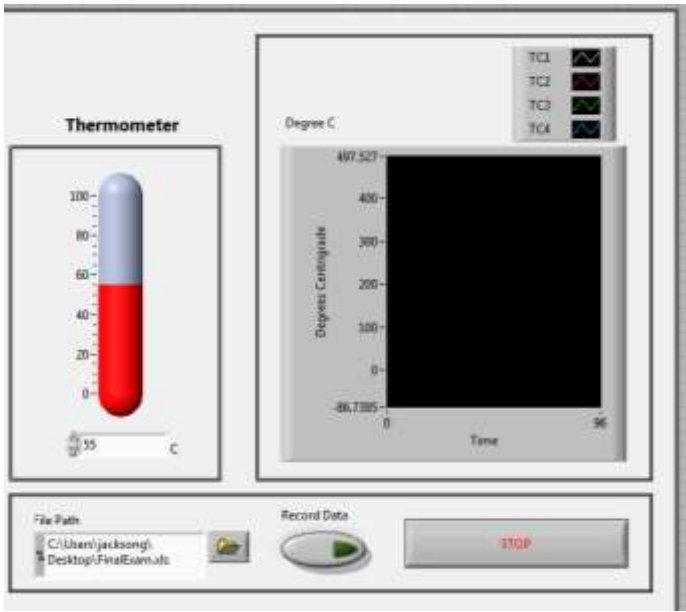
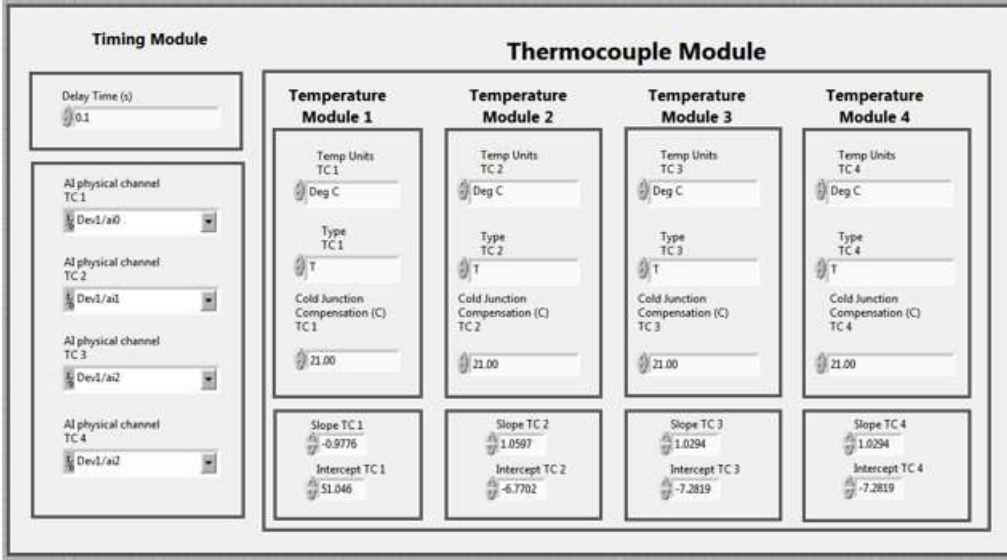


Figure 51: Front Panel of the written LabView program

Appendix D: CAD drawings of parts



Figure 52: Heater Cap CAD Drawing

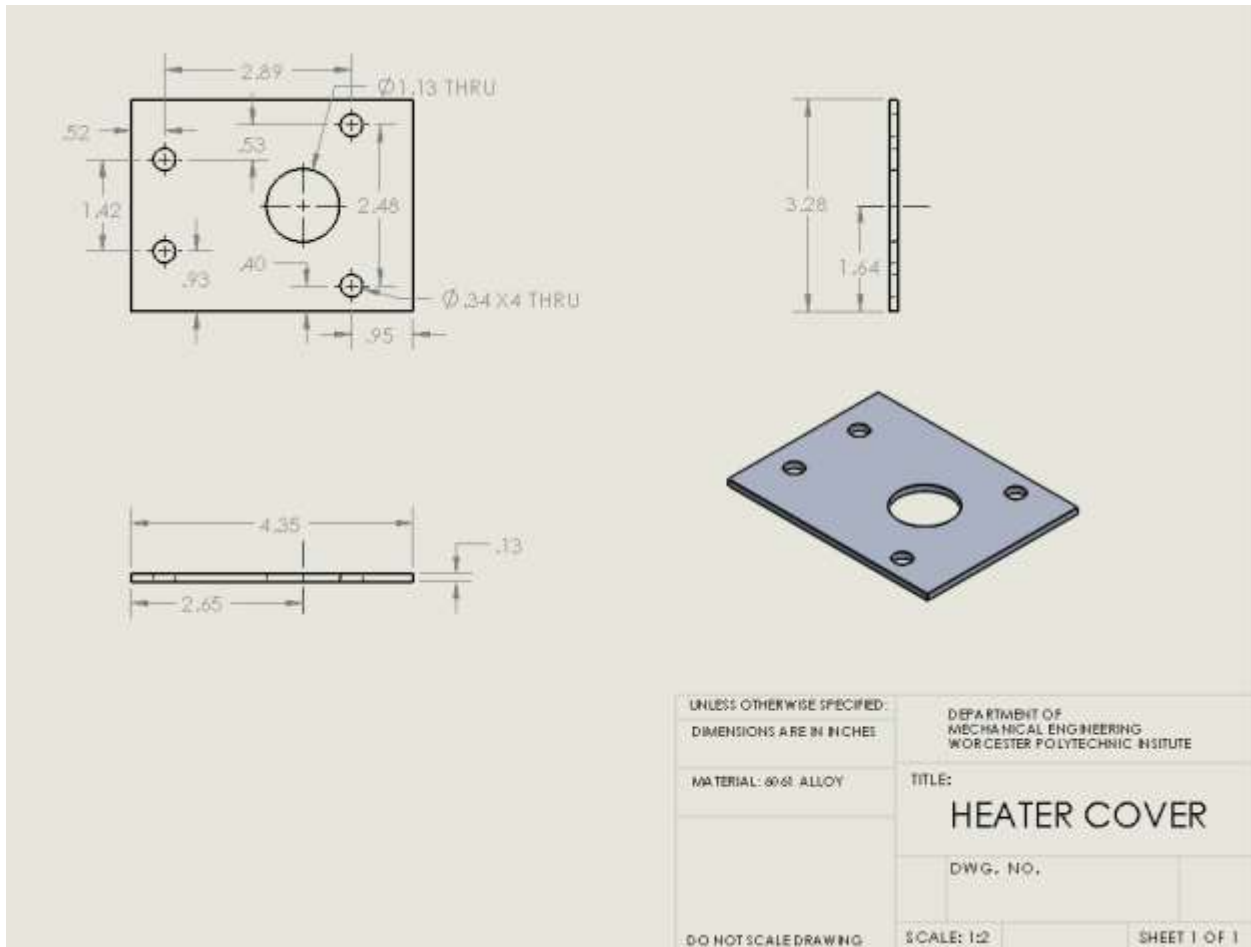
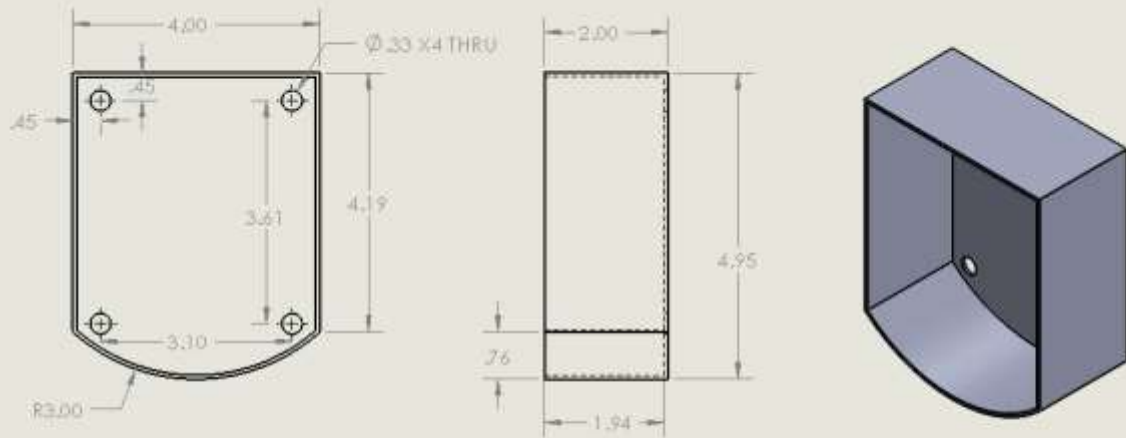


Figure 53: Heater Cover CAD Drawing

ALL WALL THICKNESS 0.0626



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES	DEPARTMENT OF MECHANICAL ENGINEERING WORCESTER POLYTECHNIC INSTITUTE
MATERIAL: 6061 ALLOY	TITLE: COOLER TANK
	DWG. NO.
DO NOT SCALE DRAWING	SCALE: 1:2
	SHEET 1 OF 1

Figure 54: Cooler Tank CAD Drawing

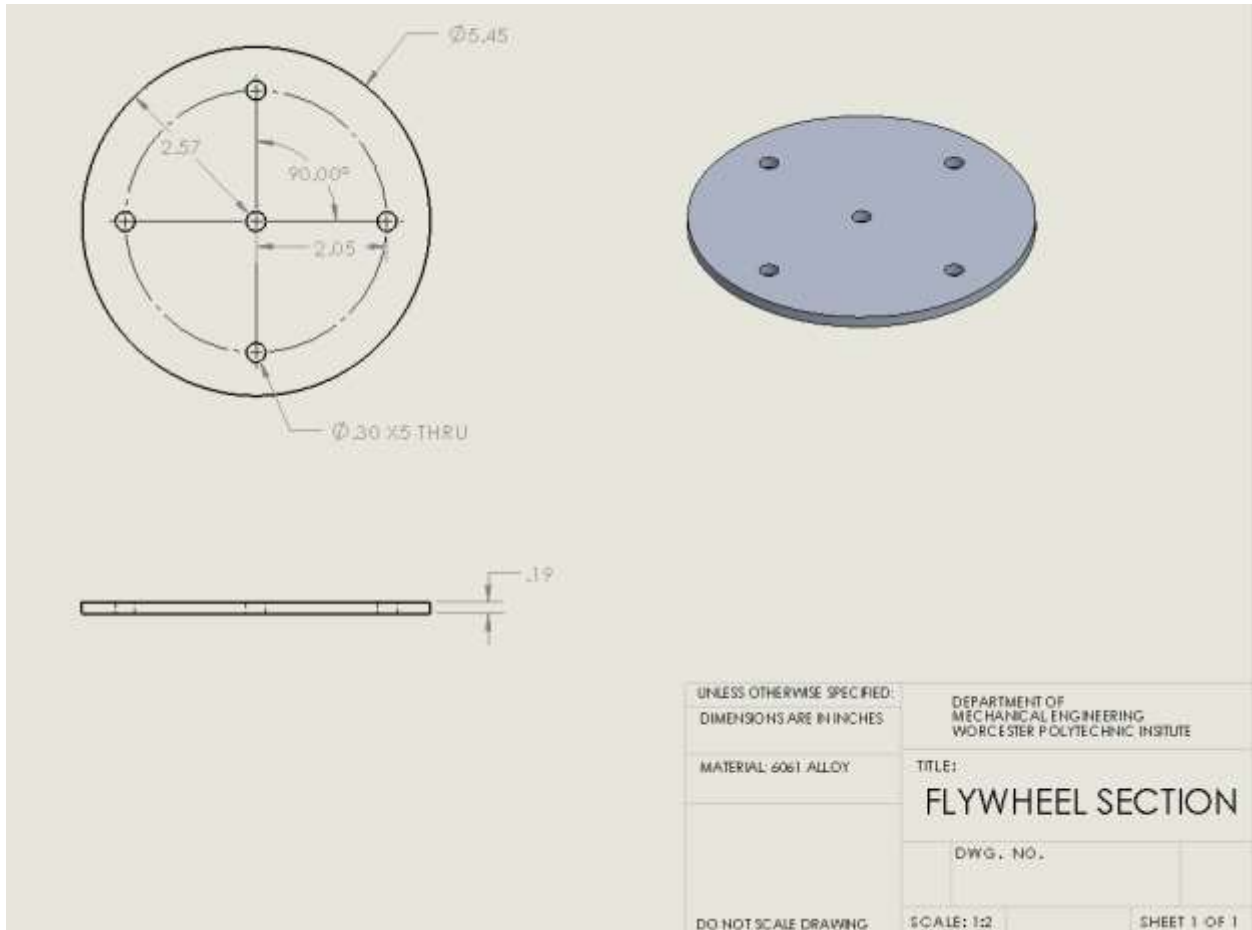


Figure 55: Flywheel Section CAD Drawing

Appendix E: Engine Assembly and Test Setup



Figure 56: Full kit of parts for the Stirling Engine



Figure 57: Testing setup for engine.