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Design and Analysis of a Stirling Engine and Practical Application

A Major Qualifying Project Report
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by

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Abstract

The project team designed, machined, analyzed, and tested a Stirling engine. The design and machining of the engine began with SolidWorks drawings and CAD files. Most machining used Haas CNC tools. The testing of the engine was completed using a modified dynamometer apparatus showing that the small engine provided low torque with high speeds. The manufactured engine was placed on the model fan boat which was also designed and fabricated by the group, but due to leakage problems was unable to power the boat. The project team theoretically demonstrated that a well-machined Stirling engine can be a suitable alternative power source for specialized applications.

Acknowledgements

We would like to thank Theo McDonald, Troy Coverstone, and David Willens for helping us with the machining of our parts. We would also like to thank everyone in the Mechanical Engineering Department, especially Tracey Coetzee for their help during Project Presentation Day. Finally, we would like to thank our Advisor, Professor Savilonis for helping us reach the end of the road.

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Executive Summary

The project team designed, machined, analyzed, and tested a Stirling engine. A Stirling-cycle machine is a device which operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of a gaseous working fluid and where the flow is controlled by volume changes (Walker, 1973). Simply, heat applied to the cylinder head causes the gas inside to expand, pushing the working piston. The air then moves through the regenerator as the displacement piston moves in the opposite direction. Heat is stored in the regenerator, and the gas then contracts. The gaseous volume is further reduced by compression and cooling at constant temperature. To complete the cycle, the gas picks up heat in the regenerator as the displacement piston moves (Zarinchang). The design and machining of the engine began with SolidWorks drawings and CAD files. Most machining used Haas CNC tools.

Once the engine was machined, it was tested for power output applying dynamic motion equations. The team developed a "dynamometer" using a digital tachometer and a digital mass balance to calculate the engines performance. The engine block was secured in a vice and lined up with the tachometer. The tachometer was secured onto the mass balance. The engine block in the vice was placed on a drill press table which had a hand crank that allowed the team to raise and lower the height of the engine. The engine was raised until the flywheel created contact with the tachometer. With this configuration, the team was able to determine the force applied to the engine and the respecting revolutions per minute (RPM) of the engines' flywheel. Once the engine was started, the flywheel was allowed to reach a constant speed, and the tachometer provided digital readings which the team recorded onto a data sheet. To calculate power and torque, our measured and recorded data had to first be manipulated. The mass balance measured

the amount of mass exerted on the flywheel, in grams, and the tachometer measured meters/minute. With this, the team converted the mass in grams to force in Newtons, and meters/minute to RPM. This data allowed for the calculation of torque and power and showed that the small engine provided low torque with high speeds.

The team recorded values from both the tachometer and the mass balance during test runs. A total of 10 tests for each of the three different masses were completed. The team experimented with high and low masses/forces, but found that too little mass led to periods of non-contact with the tachometer and flywheel, and too much mass led to a complete stoppage of the flywheel. The results from the testing showed that the team was able to manufacture a high speed, low torque engine which satisfied one team goal. The power results also showed that the engine would be able to supply enough power to force the fully designed and manufactured boat into motion.

Based on the work outlined above, the team concluded that a working Stirling engine for a model boat based on CAD designs could be manufactured. Part of the original design made use of fins for the engine. However, no fins were included in the final design due to their low fin effectiveness. The fin efficiency was calculated to be around 2% meaning that the team would have to enlarge the fins by about 50%, and consequently, enlarge the engine proportionally. This idea was not feasible in the given timeframe, so the group decided to scrap the fins for the final design.

Overall, the engine did produce an average maximum engine power output of 0.171 watts which would be more than enough power to put the boat into motion even using conservative values in the boat design calculations. However, the final resulting Stirling engine powered model boat was unable to function properly due to multiple reasons. The group believed that there was a leak at some point in the regenerative cycle which caused the engine to lose a significant amount of power. Also, the brass linkages that the group used for the engine were not perfectly aligned due to the fact that they were not machined. Rather, the team combined two shorter linkages in an effort to simulate a machined linkage. This effort resulted in a point in the rotation of the flywheel where the linkages locked up and became static. The team altered the phase change of the linkages, but could not find an angle that would work.

As a result of the problems with the engine, the team recommended that future work be completed including an analysis of the engine to discover the exact points where leakage occurred. The group also felt that designing and machining brass linkages would allow the engine to function properly without reaching a static point. The team did conservative analysis for the boat design to determine how much power would be needed, but further analysis could be completed for the desired engine size based on precise boat velocity and engine based specifications. The team also had the opportunity to discuss the project with an employee of the DEKA Company who works with Stirling engines on a much larger scale. Further conversations with this company about their refinements used with Stirling engines would prove invaluable in solving the problems experienced with this project.

1 Introduction

In 1816, a 26 year old Minister in the Church of Scotland, Reverend Dr. Robert Stirling, of Cloag, Methvin, Perthshire (Figure 1-1), invented the first closed-cycle regenerative air engine, commonly known as the Stirling engine, at Galston, Ayrshire (Finkelestein).

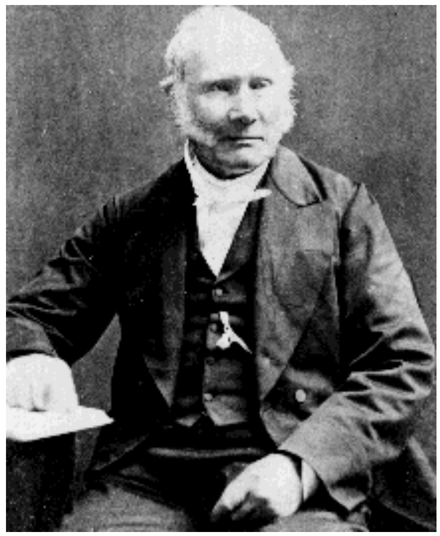

Figure 1-1 Rev. Dr. Robert Stirling
(http://www.cse.iitk.ac.in/~amit/courses/371/abhishe/stirli.gif)

A Stirling-cycle machine is a device which operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of a gaseous working fluid and where the flow is controlled by volume changes (Walker, 1973). Stirling engines incorporate a novel component, the thermal regenerator, a form of heat exchanger acting as a thermodynamic sponge alternately accepting and rejecting heat to and from the working fluid and thus, recycling a major fraction of the energy flow from one cycle to the next. Simply, heat applied to the cylinder head causes the gas inside to expand, pushing the working piston. The air then moves through the regenerator as the displacement piston moves in the opposite direction. Heat is stored in the regenerator, and the gas then contracts. The gaseous volume is further reduced by compression and cooling at constant temperature. To complete the cycle, the gas absorbs heat in the regenerator as the displacement piston moves (Zarinchang). A crude drawing of an early Stirling engine design is show below in Figure 1-2. The regenerator is the reason for Stirling machines having very high thermal efficiencies between given temperature limits (Walker, 1994). It should also be noted that Stirling machines are unique in the way they can operate as power systems, refrigerators, or heat pumps without need for modification to the machine.

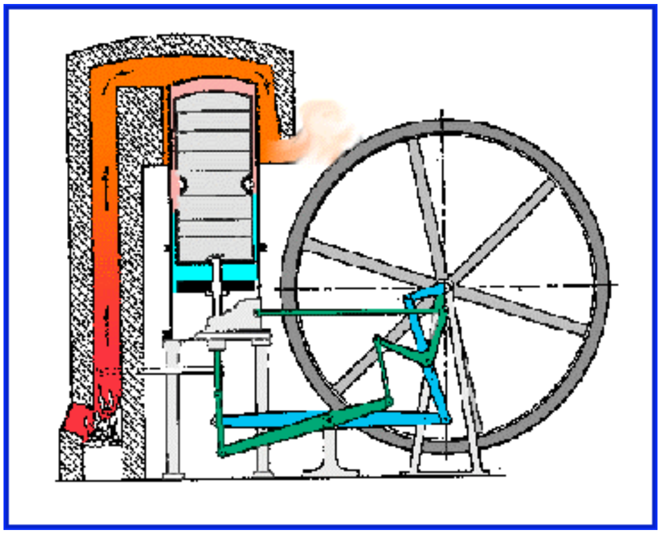

Figure 1-2 Original Stirling Engine Design
(http://www.moteurStirling.com/airchaud1.gif)

Stirling machines can also operate on an open regenerative cycle. Ericsson-cycle machines use valves to control the fluid flow in an open cycle. These open regenerative cycle machines are technically not Stirling machines, but in practice, all regenerative cycle machines, whether open or closed, are commonly considered Stirling engines. In the early 1950's, Rolf Meijer, Head of the Stirling research group at Philips Laboratories in Eindhoven, coined the generic name "Stirling engines" (Walker, 1994). Consequently the term Stirling machine or Stirling engine is a generalized definition combining a broad range of machines, each with different functions, characteristics, and configurations (Walker, 1973).

Although the two names, Stirling-cycle machine, and Stirling engine are frequently interchanged, it is important to realize that a Stirling-engine does not work on the Stirling cycle.

It is also important to note the differences between Stirling engines, where flow is controlled by volume changes, and Ericsson engines, where flow is controlled by valves. These two engines, although both are considered to be Stirling engines, are characteristically very different (Walker, 1973). Stirling engines are also referred to as hot-air or gas engines. Other names including Heinrici, Robinson, or Rankine are associated with specific arrangements of Stirling engines (Walker, 1994).

Figure 1-3 below shows the ideal Stirling cycle (green) compared to the actual cycle of a Stirling engine (red). The team's engine engine will be more similar to the red PV diagram.

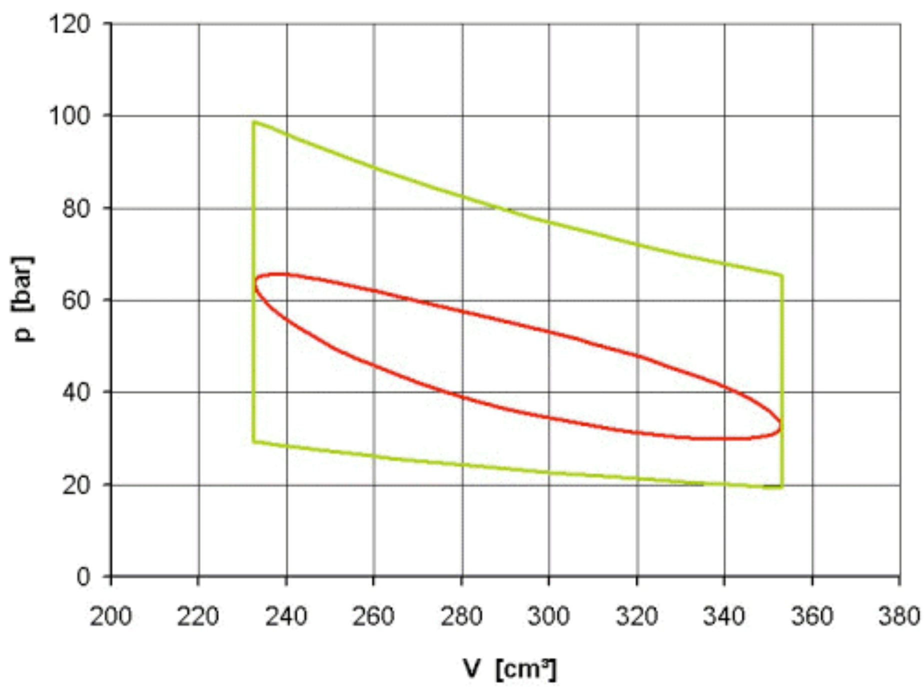

Figure 1-3 PV Diagram for Ideal and Actual Stirling Cycle

2 Background

2.1 Advantages and Disadvantages of Stirling Engines

Stirling engines are potentially friendly to the environment. With the growing concern of Global Warming and the diminishing of fossil fuel resources, there is now a greater need than ever to seek alternative power sources. Stirling engines have many advantages and disadvantages as listed below in Table 2-1. Stirlings can be fueled by numerous energy sources, such as biomass fuels and solar energy making them a cleaner and more versatile power source. Stirlings can run on combustion heat from gaseous or liquids fuels, solar heat, stored heat such as lithium fluoride batteries, and nuclear heat. Stirling's also have the potential to operate quietly since there are no valves or periodic explosions. Due to these qualities, Stirling engines are ideal for many applications.

ADVANTAGES	DISADVANTAGES
Multi-fuel Capability	Manufacturing Costs
Quiet Operation	Seal Reliability
Flat Part-Load Characteristics	'Radiator' Size
Low Pollutant Emissions on fuel source	Complex Control System
Low Cyclic Torque Variation	
Low Lubricant Consumption	
Low Internal Wear Rates	
Variety of Design	
Refrigeration without CFCs	

Table 2-1 Advantages and Disadvantages of Stirling Engines (Walker)

Stirling engines, although having many positive qualities, have their disadvantages. The primary downfall of the Stirling engine is its manufacturing costs. Research conducted in the 1970's estimated that a comparable Stirling engine would cost 50-60 percent more than an internal combustion engine. In addition, to manufacture a Stirling engine with a reasonable level (30%) of thermal efficiency, expensive and non trivial manufacturable materials must be used (Walker).

Another substantial problem encountered with Stirling engines is sealing the cylinders. It is not so important with air-Stirlings because air has a relatively high density, but Stirlings that use low density gases such as helium or hydrogen cause complications. Despite much effort, research and money, completely adequate seals for light gas, high power density Stirling engines are not readily available (Walker).

2.2 Marine Applications

Stirling engines have great potential for a vast array of marine applications. Although today the only mainstreamed use of Stirling engines for marine application is for submarines, the engine's characteristics make it a promising power source for other marine applications. Marine Engineers have researched and developed a few promising Stirling designs such as a primary mover for a large freight vessel.

Kockums Submarine Systems, a Swedish Company, is at the leading edge of naval technology and practical Stirling design and utilization. Kockums, part of the ThyssenKrupp Marine Systems, designs, builds, and maintains submarines and naval surface vessels that incorporate the most advanced stealth technology including the Stirling Air Independent Propulsion (AIP) system, shown in Figure 2-1.

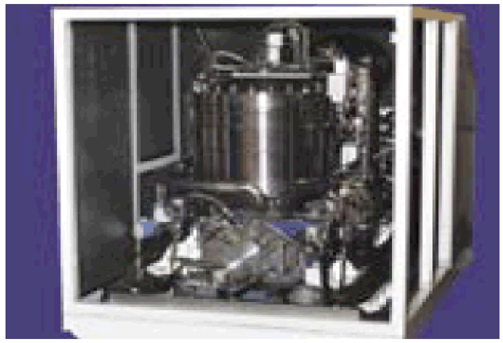

Figure 2-1 Kockums' AIP System

In 1988, Kockums installed the world's first AIP system for use in a conventional submarine. Today, the system has logged over thousands of hours and has proven highly successful as an auxiliary propulsion system for submarines weighing up to several thousands of tons. The Stirling AIP system is the most widely used propulsion system of this type. It extends submerged endurances from a few days to several weeks, a feat once limited to nuclear powered submarines. Stirlings are great candidates for underwater AIP systems because of their low noise and exhaust emissions, and their high efficiencies and multifuel capabilities.

The Swedish Fleet currently has all operational submarines equipped with AIP systems which are unique among navies using non-nuclear submarines (www.kockums.se).

Hirata and Kawada, two Japanese marine engineers, explained their ideas of Stirling power for marine applications at the 7th International Symposium on Marine Engineering in Tokyo. The two marine engineers detailed the possibilities of Stirling engines being capable of powering large vessels as well as serving as heat recovery systems. Kockums has developed a hybrid Stirling Engine – Generator system which is run underwater to trickle charge the vessel's batteries. The Stirling is fueled by a pressurized combustion system in which a mixture of hydrocarbon fuel and oxygen is burned (Walker).

Currently no Stirling engines large enough to produce comparable power to that of large marine diesel engines have been developed. Therefore, Hirata and Kawada theoretically built an eight cylinder Stirling engine capable of producing 20,000kW using performance prediction methods and similarity rules (Hirata and Kawata) shown below in Figure 2-2. Since the engine was not actually built, only minimal analysis of the performance, efficiency, and feasibility of the application could be taken. Immediate problems found by analysis is that the Stirling engine is double the width of the diesel engine and due to extremely high pressures in the Stirling, it would have to be constructed out of high strength materials (Hirata and Kawata).

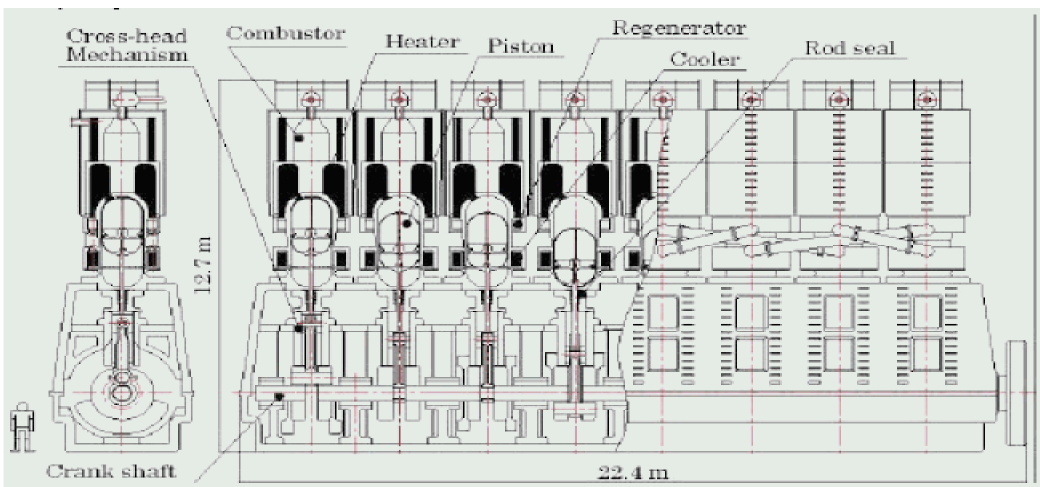

Figure 2-2 Theoretical 20,000 kW Stirling Engine

Another marine application for Stirling engines is for heat recovery systems in conjunction with the vessel's diesel engine. The principle theory is that the Stirling engine is fueled by the diesel's excess exhaust heat to produce auxiliary power as an alternative to diesel generators. This theory has been a project in Japan since 2005 sponsored by the Japan Railways Construction, Transport and Technology Agency (JJRTT) (Hirata and Kawata). The Stirling engine is small, producing about 5 kW of power. When the vessel is in operation the batteries are constantly being charged so when the vessel is in port the batteries supply clean and quiet electric power as shown in the schematic below in Figure 2-3 The prototype Stirling engine for this application is displayed in Figure 2-4.

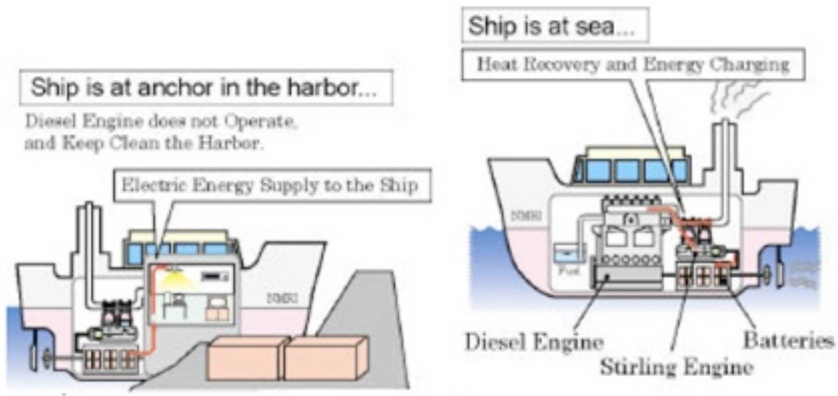

Figure 2-3 Heat Recovery System

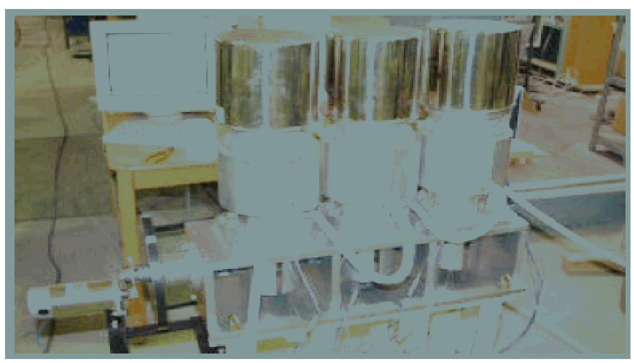

Figure 2-4 Prototype Stirling Engine for Heat Recovery System

2.3 Solar Applications

In the Unites States, Stirling Energy Systems (SES) is a systems integration and project management company that is developing equipment for utility-scale renewable energy power plants and distributed electric generating systems, “genset” for short (www.Stirlingenergy.com). SES is positioned to become a premier worldwide renewable energy technology company to meet the global demand for renewable electric generating technologies through the commercialization of its own Stirling cycle engine technology for solar and genset, (generator system) applications (www.Stirlingenergy.com).

In 1996, SES acquired the patent, tooling, and equipment rights to the world's most efficient solar dish concentrator system: the Dish Stirling (Figure 2-5). Initially developed in the 1980s by McDonnell Douglas (now The Boeing Co.) the Dish Stirling system was field-tested by Southern California Edison and Georgia Power for over 175,000 hours between 1982 and 1988 (www.Stirlingenergy.com). Edison's test data indicated the Dish Stirling out-performed all other solar-to-electric generating systems by a factor of two, yet had comparable start-up costs. SES optimized the McDonnell Douglas dish to operate with a 25kW Stirling power conversion unit (PCU) developed in Sweden by United Stirling, Kockums and Volvo. The resulting system, the "Dish Stirling", has fewer moving parts than comparable diesel engines and operates relatively quietly (www.Stirlingenergy.com).

SES is in the forefront of developing alternative solar energy and is currently testing its prototype solar dish field in New Mexico. Each dish has two major components, the solar concentrator and the power conversion unit (PCU). The 25kW SES Dish Stirling system has an operating track record of more than 17 years. Since 1984, it has held the world record for efficiency in converting solar energy into grid-quality electricity (www.Stirlingenergy.com).

The solar concentrator is a large parabolic dish lined with 89 mirror facets, as illustrated in Figure 2-5 below. The mirrors are precisely aligned to concentrate the suns solar energy to the PCU. The dish is equipped with two motors which allow the dish to swivel and rotate to follow the suns progress across the sky throughout the day. The system begins at sun rise, automatically aligning itself with the sun and follows it until sunset when the system enters “night-stow” with the engine at ground level (www.Stirlingenergy.com).

Figure 2-5 SES Solar Dish Stirling System
(http://www.Stirlingenergy.com/photos/photo/SES1666x1638.jpg)

The dish's PCU, a Stirling engine, consists of four sealed cylinder assemblies with coolers, regenerators and heater heads. The cylinder assemblies consist of pistons, piston rods, and connecting rods domes (www.Stirlingenergy.com). The solar energy concentrated from the mirrors fuels the Stirling engine containing hydrogen gas. The engine cycles at a steady rate of 1,800 rpm running an electric generator producing an output voltage of 480 volts at 60 Hz. In a utility-scale plant, the Stirlings are connected to a substation where the power is conditioned to be transferred across the power grid (www.Stirlingenergy.com). SES predicts the dish solar Stirling systems to most likely be marketed outside of the United States to countries with strong government commitments to alternative energy sources.

2.4 Automotive Applications

Stirling engines can be used as alternatives to internal combustion engines in automobiles, but may be considered impractical since gasoline engines are so abundant, cheap, and reliable. Although the internal combustion engine appears to be the superior choice for automotive power, Stirlings still give the gasoline engine some competition. For example, Stirlings are nearly silent during operation, produce very little exhaust, and as stated earlier, can operate on a wide range of fuels.

The transportation sector is the dominant oil consumer in the United States, accounting for more than 60 percent of the nation's oil demand and using more than is domestically produced. Passenger cars consume over one-third of the transportation energy (www.nap.edu). Because of the high demand for fossil fuels in the transportation sector and a diminishing supply, automotive companies have researched and developed automotive Stirling applications for decades.

In the 1970's, Ford, General Motors and American Motors Corporation (AMC) spent millions of dollars researching and developing Stirling powered automobiles. AMC installed the 'P-40' Stirling engine into the AMC Spirit, sub-compact automobile. The Spirit could run on gasoline, diesel, or gasohol with less pollution, better mileage, and at the same level of performance of the standard internal combustion engine (www.Stirlingengine.com). However, the overall research proved disappointing, and when oil prices plummeted, so did Stirling engine development for automobiles. Research and development picked back up in the 1980's and then again in the 1990's, proving successful technologically, but not so successful in the areas of manufacturing, marketing, and public interest.

3 Methodology

For this project we investigated the mechanisms of how a Stirling engine works and experimentally showed these principles. Since 2000, numerous students have taken ME 1800, a mechanical engineering course at WPI and have assembled Stirling engines. However, these students have not investigated the thermodynamics, heat transfer, or kinematics behind these engines.

For our design, we mathematically displayed the inner workings of the engine. We showed how much power will be transferred to the flywheel based on the amount of heat entering the heating sleeve. Once this was done, the engine was tested to demonstrate that it can perform in the real world based on our theoretical design. Our ultimate goal was to power a model boat by our engine. Since our model boat has an insignificant drag force, low density, and low mass, a small engine will suffice. Therefore, the design team decided to use a stirling engine with the specifications of the ME 1800 stirling engine.

3.1 Design and Machining of the Engine

Originally, the team was going to analyze and test the engine built in ME 1800, and if this design proved inappropriate for our boating purposes, then we would machine our own. However, we found a nearly completed MQP similar to our own, in which a team was designing a new Stirling engine for ME 1800. Currently, the engine built in ME 1800 is from a kit and the engine needs only a base and a flywheel to be machined for it. The new engine from this MQP group was completely machined here at WPI. This new engine had yet to be tested or analyzed. The focus of that project was manufacturing. We planned on analyzing this engine for power instead of using the kit from ME 1800.

We wanted to modify the design of the previous engine as needed. For example, if the engine were not powerful enough, we could simply increase the dimensions of the design. However, once we started designing and modifying their engine, we soon developed a very different engine design. Our design was smaller and lighter and in addition contained a finned heat sink to disperse heat better. The only similarity now between the two engines was the fact that both use the pistons and heating sleeves from the ME1800 kit. This was because these parts are very difficult to machine. Another difference between the two engines was the machining process. Our group was using high speed helical boring and the previous group used reaming tools.   Since an engine very similar to ours will be replacing the kit here at WPI, analyzing the new engine would be useful to the school.

The engine block was based on the two pistons from the ME1800 kit. This was because WPI does not have the manufacturing capabilities to make sealed, hollow pistons. The best that could be done would be to machine light weight aluminum pistons. However, due to the wear properties of aluminum, the seals formed by the pistons would degrade quickly, resulting in a loss of power to the engine.

The team designed Stirling engine was a gamma type engine which houses one power piston (Institute of Reciprocating Engines). It is a gamma type because the engine contains one power piston and one displacer pistons in separate chambers. The engine also contained five fins on the heat exchanger. The team designed the engine so that any unnecessary material has been machined away, reducing weight significantly (Figure 3-1).

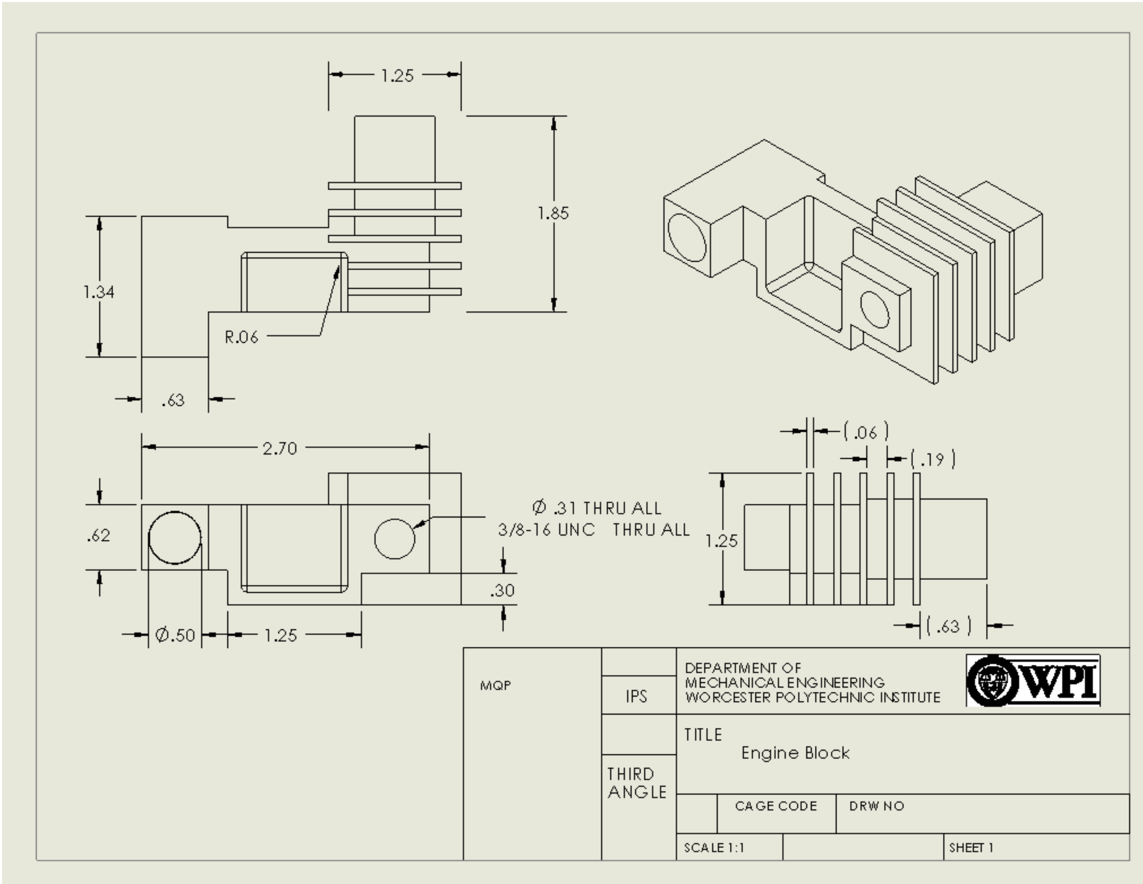

Figure 3-1 CAD Drawing for Engine Block

The engine was mostly machined from aluminum because of its low cost and light weight. Due to aluminum's lower heat capacity, steel was used for the heating sleeve.

The engine was supported by an aluminum base which also supported the propeller. The base was 5.67 inches long. This distance was chosen based on the size of the engine block and the maximum spacing needed for the largest possible propeller. The engine block had two bolts which were driven through the top of the block, through the base and into the boat. These bolts connected all three necessary pieces: the engine, base, and boat. Figure 3-2, Figure 3-4, Figure 3-4, Figure 3-5, Figure 3-6, Figure 3-7, Figure 3-8 are CAD Drawings and SolidWorks Models of the final engine design and assembly.

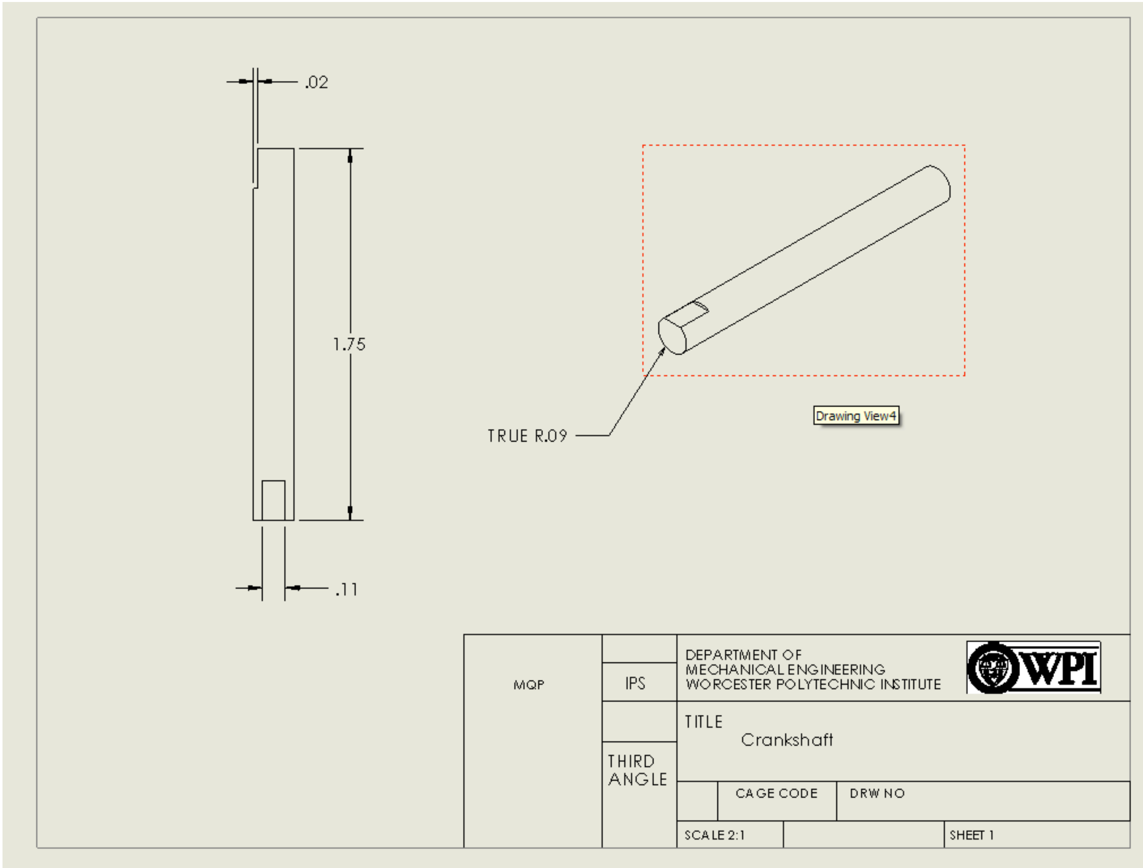

Figure 3-2 CAD Drawing for Crankshaft

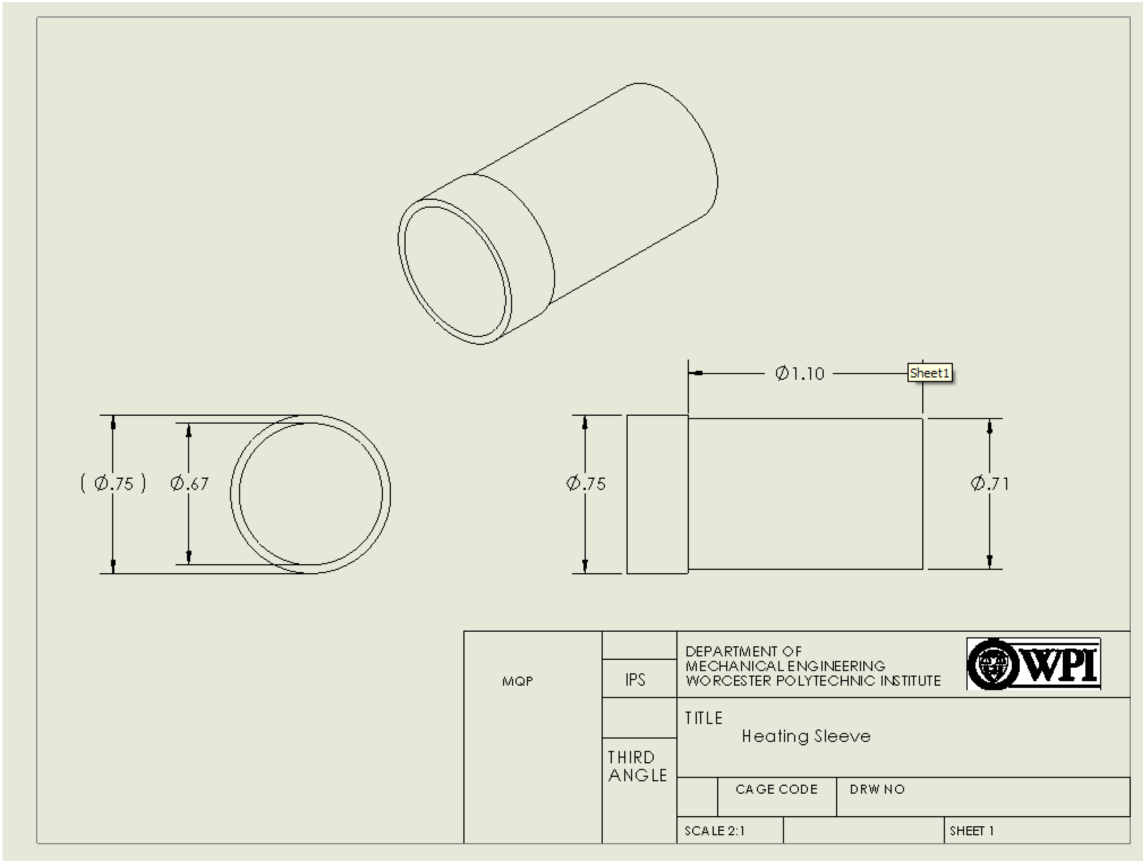

Figure 3-3 CAD Drawing for Heating Sleeve

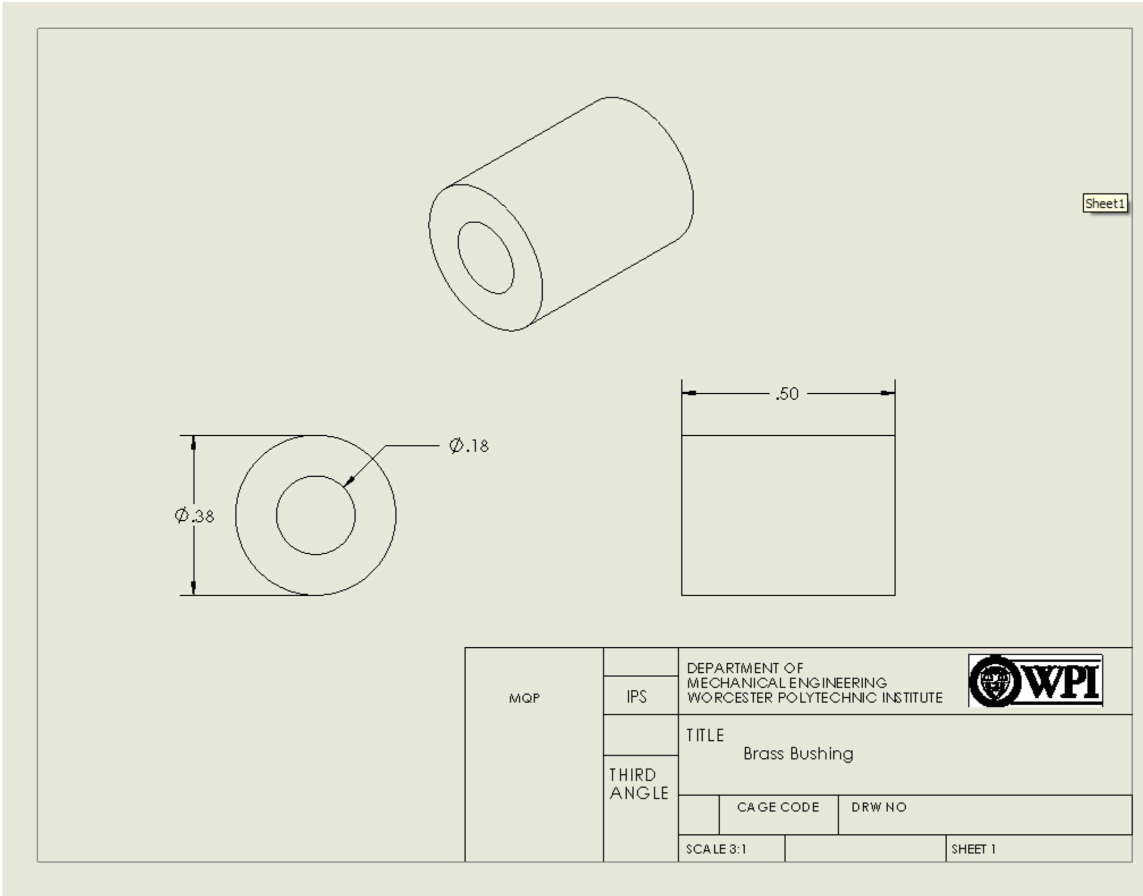

Figure 3-4 CAD Drawing for Brass Bushing

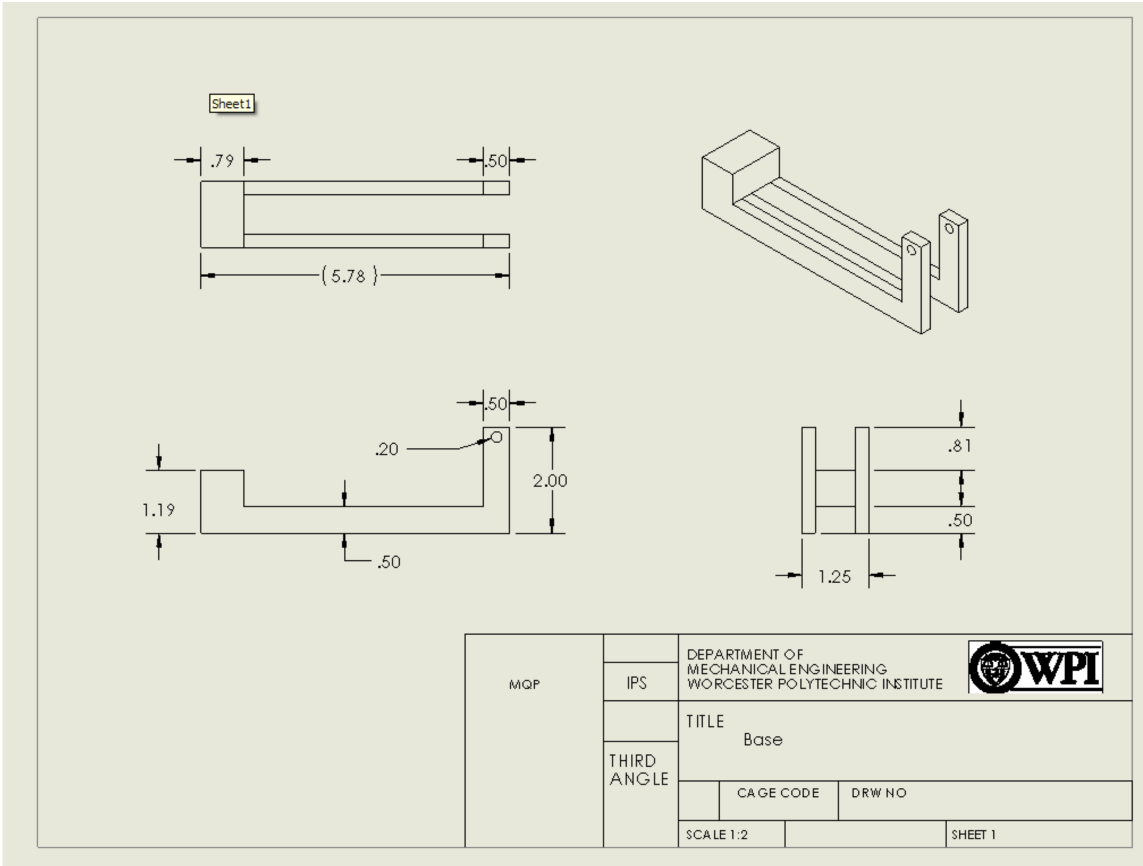

Figure 3-5 CAD Drawing for Engine Base

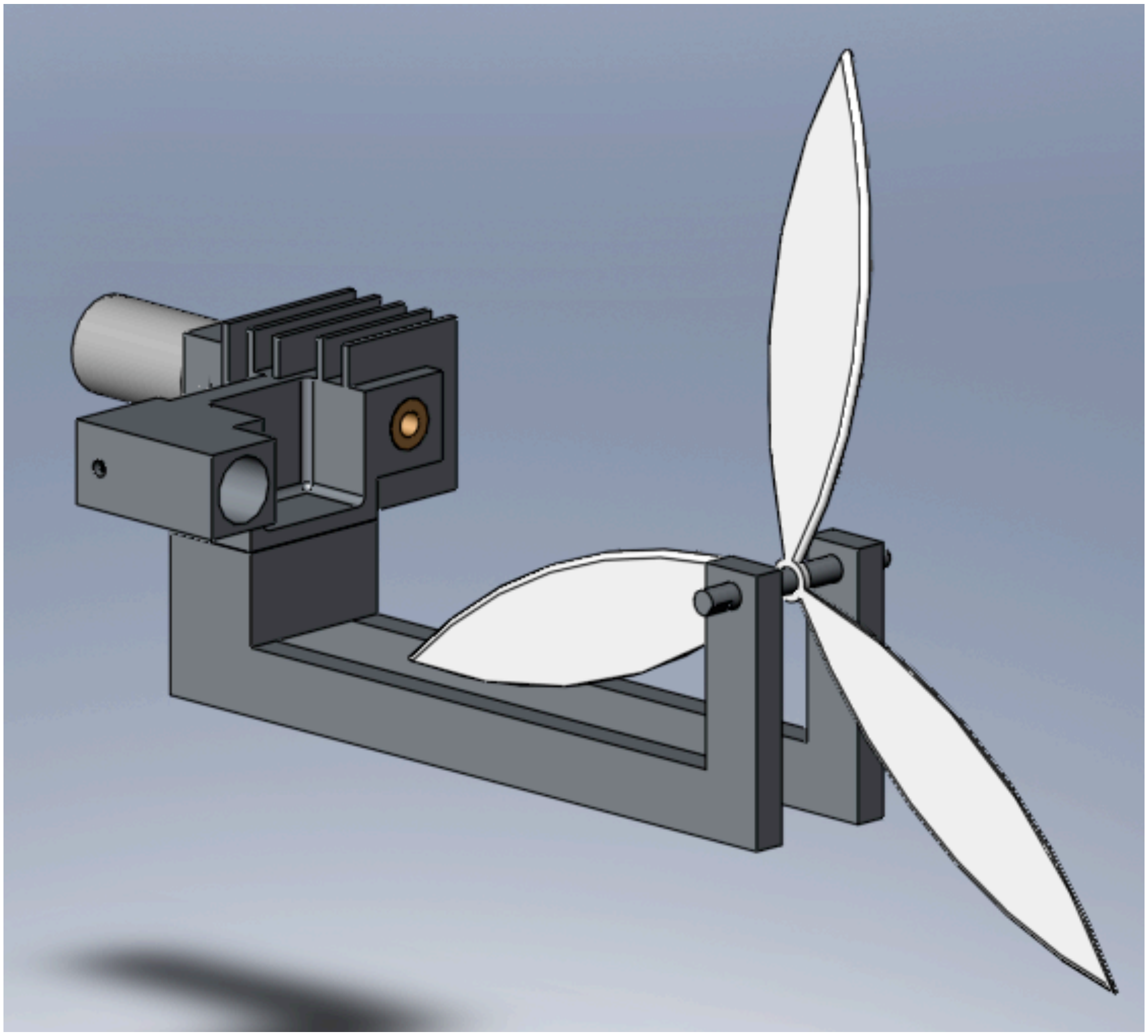

Figure 3-6 SolidWorks Model of Completed Engine

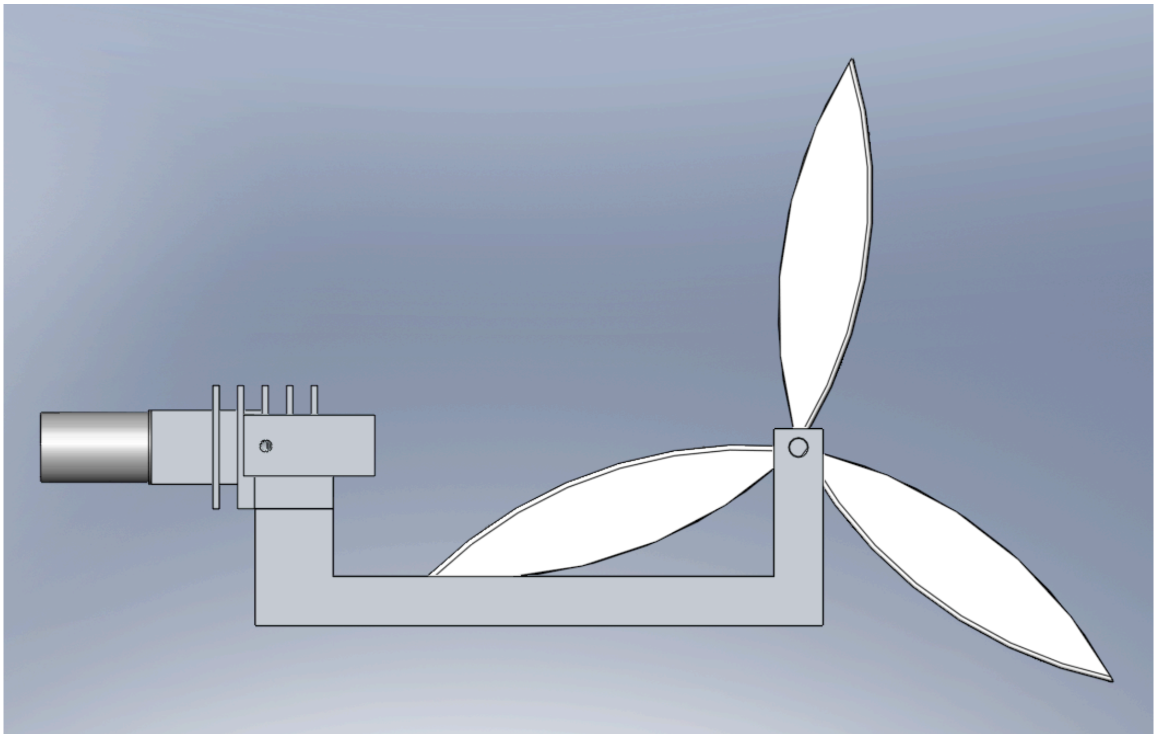

Figure 3-7 Side View of Completed Engine

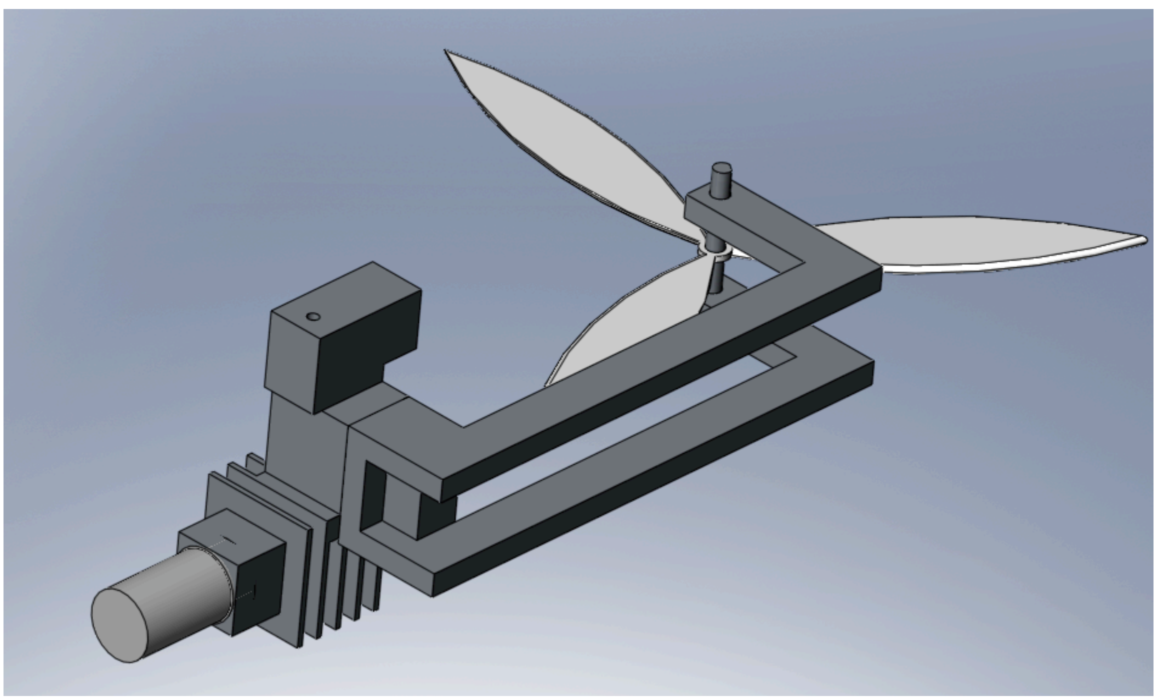

Figure 3-8 Alternate View of Completed Engine

3.2 Fins

Fins are attached to heatsinks to improve performance by enhancing the convective heat transfer between the solid and the adjoining fluid which in this case is air. There are three ways in which the heat transfer rate may be increased. The convection heat transfer coefficient, h, could be increased by raising the fluid (air) velocity, the air temperature could be reduced, or the heat transfer rate may be increased by increasing the surface area across which the convection occurs. Increasing fluid velocity can be achieved by adding powerful fans or pumps which can be costly. Decreasing the fluid temperature is often impractical as well. However, increasing the surface area is an easy solution. Fins extend from the wall of the heatsink into the surrounding fluid which increases the surface area. Ideally, the fin material should have a large thermal conductivity to minimize temperature variations from the base to the tip (Incropera et al, 2007).

3.2.1 Materials

The two most commonly used materials when designing a heatsink are aluminum and copper. The thermal conductivity of the heatsink's material has a major impact on cooling performance. Thermal conductivity is measured in W/mK; higher values mean better conductivity. Alloys have lower thermal conductivity than pure metals, but may have better mechanical properties (Heatsink-guide.com).

Aluminum is a relatively cheap material with good thermal conductivity. The aluminum alloy 2024-T6 has a thermal conductivity of 168 W/mK at 300 Kelvin (Incropera et al., 2007). Because of its softness, aluminum can be a manufactured by extrusion techniques which further lowers cost (Enertron).

Copper's thermal conductivity is about twice that of aluminum. Pure copper has a thermal conductivity of 401 W/mK at 300 Kelvin (Incropera et al., 2007). This is very high, but because of the purity of the metal, production costs increase. Another disadvantage of copper is its weight which can add stresses to mounted components. Copper's production techniques differ from that of aluminum as well. Copper heatsinks cannot be extruded and are made by milling or die-casting. Even though copper can transfer heat more effectively, because of these disadvantages aluminum is the main choice for heatsinks. However, if a higher rate of transfer is needed heatsinks may contain both copper and aluminum (Heatsink-guide.com).

3.2.1.1 Aluminum vs. Copper

Aluminum is the most common material used for heatsink or conducting material for many good reasons. It possesses a high thermal conductivity, is easy to form and machine, and is quite light (Keller, 1998).

Pure copper has an extremely high thermal conductivity but, even to a more extreme than aluminum, the impurities needed to make casting or machining possible drop its conductivity, even more drastically than aluminum. It can be seen in Table 3-1 below how these impurities drastically affect the thermal conductivity of copper (Keller, 1998).

	Pure Copper	Al Bronze	Bronze	Red Brass
Conductivity	386 W/mK	83 W/mK	26 W/mK	61 W/mK
Composition	100% Cu	95% Cu, 5% Al	75% Cu, 25% Sn	85% Cu, 9% Sn, 6% Zn

Table 3-1 Copper Alloy Comparison

When using a copper heatsink, casting or machining causes problems because pure metal is desired. Keeping the metal pure raises the cost of the component. In order to properly manufacture a copper heatsink, machining from a flat plate with fins or other features brazed in place must occur. Also, machining copper wears out equipment quickly due to its density and abrasive nature. The whole process is long and as a result costly.

So it would seem that cost is the driving force behind material selection for a heatsink. While this is part of the equation, there are times when to use copper and when not to. Simply, if the properties of aluminum will provide enough cooling, then copper is unneeded and the extra cost is a waste. However, extra cooling may be needed (Soule, 2001).

"Many designers will turn to copper as an alternative material to improve heat sink performance when an aluminum sink may not provide enough cooling. In some cases this switch is justified, in other cases it may not be. The following are a few rules of thumb for when the extra cost and weight of copper makes sense" (Soule, 2001). The following paragraphs explain these rules.

Pure copper is about twice as conductive as extruded aluminum. This helps in dissipating heat created by a processor. However, this is only useful when air flow speeds are very high being over 800 linear feet per minute and when the heat input area or the hot spot on the mounting surface is small on the order of 25% or less of the heatsink base. Airflow speeds below 400 linear feet per minute and/or the heat input areas higher than 25% of the heatsink base make the extra cost of copper impractical.

An all copper pure heatsink is typically three times the cost of an equivalent sized aluminum one and although it may have an advantage in increasing heat removal and lower semiconductor temperatures, the added cost and custom nature of the part will add complexity to the system that must be considered form both the thermal and economic sides of design (Soule, 2001).

3.2.2 Fin Analysis

Some might believe that simply making a very large heatsink with many fins will increase performance. However, this assumption is wrong. Closely spaced fins will not be able to dispose of the heat properly. This is due to lack of air flow within the confined space and because the fins will radiate much of the heat to adjoining fins. The maximum distance between fins is dependent on the height of the fins (Eliot, 2003).

3.2.3 Fin Density vs. Fin Thickness

Not only are fins restricted by air movement, but also by manufacturing feasibility. The constraints on fin pitch are related to the fin folding machinery. The spacing of the fins is a function of material thickness. The spacing must be greater than some multiple of the thickness. Based on experimental methods performed by Dr. Biber and Susan Fijol, for fins up to 75 mm long and 25 to 50 mm high, the multiple was 3.0. This is illustrated in Figure 3-9 and Table 3-2. As one can see by Figure 3-9, as the fin thickness increases, the viable number of fins decreases logarithmically. This idea will be important when optimizing heat sink design (Biber and Fijol).

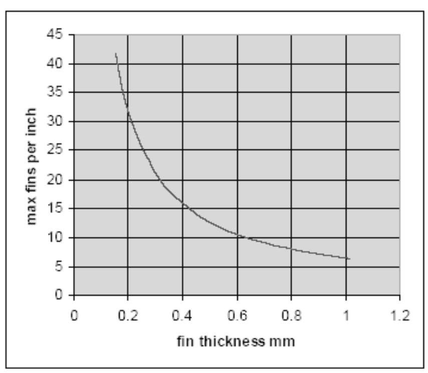

Figure 3-9 Manufacturable Fin Density vs. Fin Thickness

Fin thickness	Min. gap (3x)	Max # of fins for 75 mm flow width
0.3 mm	0.9 mm	62
0.4 mm	1.2 mm	46
0.5 mm	1.5 mm	38

0.8 mm	2.4	24

Table 3-2 Maximum Manufacturable Fin Density

3.2.3.1 Number of Fins and Height Variation

Figure 3-10 shows the optimization of thermal resistance for different fin heights in terms of the number of fins. Lower thermal resistance will improve performance. Higher resistances impede heat transfer. For the comparison, a fin thickness of 0.8 mm was chosen. Again, as the number of fins increases, the space between the fins decreases. Smaller inter-fan spacing yields an increase in the pressure drop of the system for the given volume flow rate of 1.5 mm^3. The smaller spacing will eventually impede the flow of air and resistance will rise (Biber and Fijol).

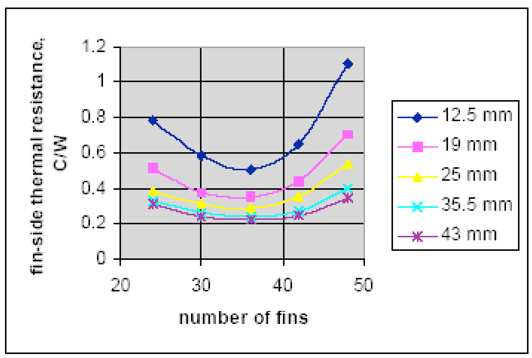

Figure 3-10 Thermal Resistance vs. Number of Fins of Various Heights

"At the high end of the range of number of fins, the volume flow rate through the small spaces is so low that air heating outweighs the heat transfer coefficient advantage of the smaller spacing, and dominates the thermal resistance. At the low end of the range of number of fins, there is simply not enough fin area to achieve high performance. These two competing effects produce the minima in the curves shown in Figure 3-10" (Biber and Fijol).

Returning to the manufacturing capabilities for fin density, in this experiment for the given heat sink of size 60 by 25 mm and fins with a height of 25 mm or higher, the maximum number of fins is 24. Therefore the experimental optimum can never be reached.

A significant result from Biber and Fijol's work is that the sensitivity to the number of fins decreases as the fin height increases. Larger flow spaces have lower pressure drops and by reducing the fin space by adding more fins, lower increases in pressure drops from the increase in fin heights is observed. This results in a lower flow rate and translates to a higher air temperature due to the thermal resistance.

Another concept drawn from these findings is that the addition of fin height brings less and less performance return. This is because of decreased air speed and fin efficiency, e_f (Biber and Fijol).

3.3 Analysis of a Stirling Engine

In order to know the amount of heat necessary to give the needed amount of power to move the boat, we needed to evaluate our design. Luckily, a Stirling engine operates on fairly basic thermomechanical principles. As stated earlier in the background section of this paper, a Stirling engine follows simple gas and thermodynamic laws. As one end of the cylinder increases in temperature, the pressure increases causing the piston to fire outward decreasing the volume. Next, heat exits the engine, pressure drops, and the cylinder returns. With these concepts in mind, we analyzed the Stirling engine.

In a Stirling engine heat enters through the heating sleeve by convection from the heat source. The heat then enters the hollow center of the sleeve by conduction. Next, the heat travels to the regenerator by conduction and then most of the heat exits through the fins by convection. Simple heat transfer occurs. When we analyzed this part of the engine and the pressure and velocity of the air inside the engine, we assumed incompressible flow for simplicity purposes.

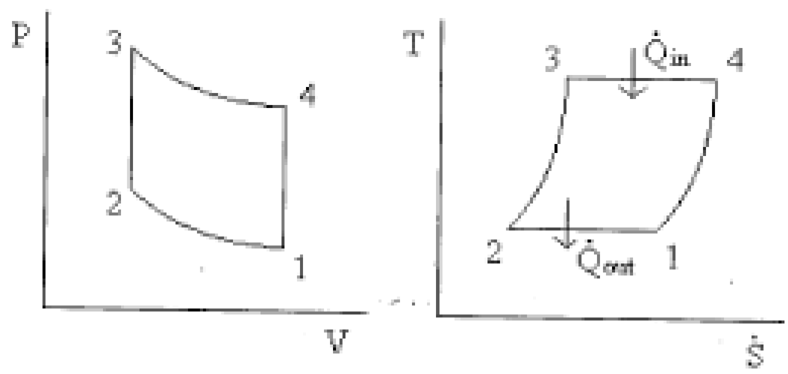

Figure 3-12 P-V Diagram

Figure 3-12 illustrates the behavior of an ideal Stirling engine. While not being completely accurate, these diagrams give an idea of the workings of the engine. The engine does not have four distinct areas of time where changes occur, nor will the temperature or volume ever be constant. Fraction 1-2 shows the volume decreasing due to low chamber pressure. This then moves the piston, increasing pressure. The temperature remains constant for this process. In true life, heat will continue to leave the engine through the fins. Fraction 2-3 is the piston moving into the heating region. This causes a rapid increase in temperature. For the engine, volume will never be constant. However, there will be times of little variation. Fraction 3-4 is the volume increasing because of high chamber pressure. Again, the temperature ideally will remain constant. However, in the real world heat will continue to enter the chamber. Finally in fraction 4-1, the volume remains constant as the piston moves into the cooling region. Heat rapidly leaves the engine (McElroy).

Our engine's power piston is mounted in a separate cylinder alongside the displacer piston cylinder, but is still connected to the same flywheel. The gas in the two cylinders can flow freely between them but remains a single body. The equations below model the mean pressure in our engine.

$P = 101.3\ kPa$

Atmospheric pressure; Pressure at which engine is at before use

P_{tot} = *Engine Pressure kPa*
V_{se} = *Swept Volume of expansion piston*
V_{de} = *Dead Volume of expansion space*
V_r = *Regenerator volume*
V_{dc} = *Dead volume compression space*
V_e = *Expansion volume*
V_c = *compression volume*
V_{tot} = *Total volume*
m_{tot} = *total mass in engine*
R = *Gas constant*
T_h = *Expansion temperature*
T_c = *Compression temperature*
T_r = *Regenerator temperature*

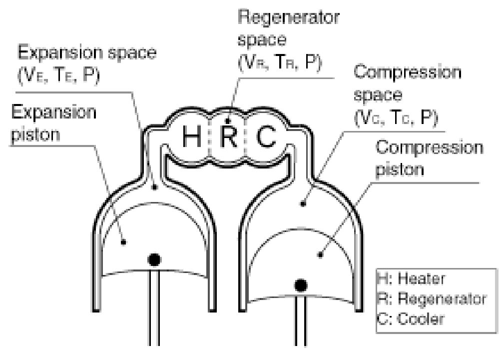

Figure 3-12

$V_{se} = 7.85 \times 10^{-6}\ m^3\ (\textit{from our design})$

$V_{de} = \frac{V_{se}}{2}$

$V_{de} = 3.93 \times 10^{-6}\ m^3$

$V_e = V_{de} + \frac{V_{se}}{2}(1 - \cos(0))$

$V_{sc} = 1.96 \times 10^{-6}\ m^3$

$V_{dc} = 7.85 \times 10^{-7}\ m^3 (\textit{from our design})$

$V_c = V_{sc}(1 - \cos(0)) + V_{dc}$

$V_r = 3.95 \times 10^{-7} (\textit{from our design})$

$V_{tot} = V_e + V_r + V_c$

$V_{tot} = 5.105 \times 10^{-6}\ m^3$

$R = 8.314$ m3·Pa·K - 1·mol - 1

$T_c = 296$ °K room temperature

$T_e = 1473$°K Temperature expansion piston due to blowtorch

$$T_r = \frac{(T_e + T_c)}{2}$$

$$m_{tot} = \frac{(P \cdot V_{tot})}{R \cdot T_c}$$

$m_{tot} = 2.101 \times 10^{-7}\ kg$

$$P_{tot} = m_{tot} \cdot R \cdot \frac{T_e}{V_e} + m_{tot} \cdot R \cdot \frac{T_r}{V_r} + m_{tot} \cdot R \cdot \frac{T_c}{V_c}$$

$P_{tot} = 5.227 \times 10^3\ kPa$

The theoretical mean pressure in the engine will be roughly fifty times that of the atmospheric pressure. This pressure is sufficient to power our small engine since the parts are very lightweight.

3.4 Testing of the Engine

Once the engine was machined, it was tested for power output applying dynamic motion equations. The team developed a "dynamometer" using a digital tachometer and a digital mass balance to calculate the engines performance.

The engine block was secured in a vice and lined up with the tachometer. The tachometer was secured onto the mass balance. With this configuration, the team was able to determine the force applied to the engine and the respecting revolutions per minute (RPM) of the engines flywheel. Figure 3-14 displays the testing setup and configuration.

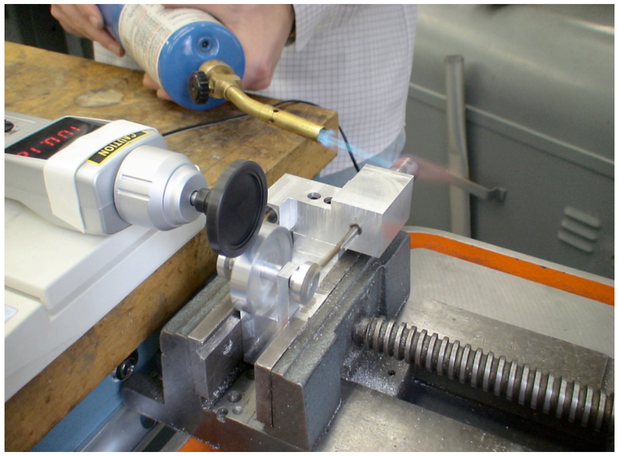

Figure 3-14 Testing with the Modified Dynanometer

The Flywheel was raised up until contact was made with the stationary tachometer. This configuration allowed the team to calculate the engine's power and torque output by correlating the force applied to the engine and the engine's RPM.

To calculate power and torque, our measured and recorded data had to first be manipulated. The mass balance measured the amount of mass exerted on the flywheel, in grams, and the tachometer measured meters/minute. With this, the team converted the mass in grams to force in Newtons, and meters/minute to RPM. This data allows for the calculation of torque and power.

Torque multiplied by the rotational speed gives power (Hibbeler, 1998). For our tests, we applied a force to the flywheel, started the Stirling engine, waited for it to achieve a constant velocity, and then measured the rotational speed with a tachometer. This measured the power of the engine.

$$\tau = torque$$
$$r = moment\ (m)$$
$$F = force(newtons)$$
$$\tau = r \times F$$
$$Power = \frac{\tau \cdot 2\pi \cdot rotational\ speed(rpm)}{60}\ (Watts)$$

Originally, we were planning to test our engine with both a chafing tool such as a sterno and a blowtorch. Since the sterno is both lighter and less expensive than a blowtorch we were hoping that it would provide enough heat to power the engine sufficiently. However, through testing of Stirling kit engines from the course ME1800, we found that the chafing fuel would not provide enough heat. Now our engine was powered solely by a miniature blow torch. This torch is rated by the manufacturer to output a 1250 degree Celsius flame (Figure 3-16).

Figure 3-16 Blow Torch

3.5 Boat Design and Fabrication

Many different boat designs are possible for this project. However, the team decided to create a boat with a twin hull. The reason for this is because a twin hull is very stable and has relatively low drag when compared to other boat designs with similar stability. The two hulls were connected at the ends by strips of wood. The engine sat on the two hulls with the propeller extending toward the middle of the boat.

Pine wood was used as the main construction material for the boat. Pine was used because of its low density. Additionally, pine is very soft and easy to handle. Another material used was foam. This material was used because of its extremely low density of .001 g/cm3. The foam made up the lower portion of the boat. We did not construct the boat entirely out of foam because of its very low melting temperature. The two hulls were constructed by cutting a base of a particular size, then cutting sequential hollowed bases of increasing size. These were stacked and glued atop one another until a hull has been created. Next the hulls were sanded, sealed, and painted.

The two main materials being used were the pine wood for the boat and aluminum for the engine. Pine has a density of about .4 g/cm3. Aluminum has a density of about 2.7 g/cm3 (Shackelford 2005). Assuming these are the only two materials being used, the boat will need to have roughly 3 times as much volume as the engine to displace the water and keep the boat afloat.

The engine was placed on one hull and connected by bolts. The machined base will extend toward the midpoint between the two hulls. The two hulls were connected by square wooden dowels.

Finally, the boat housed robotic controls for the steering of the vessel. These directed a rudder at the rear of the boat. We used a Hitec 2-way radio and 5 kg servo to control the rudder. The rudder was remotely controlled much like a radio controlled toy car. We used a Hitec 2-way radio and 5 kg servo to control the rudder. Sample construction of the hull is shown below in Figure 3-18.

Figure 3-18 Wood Hull Construction

3.5.1 Hull Design

The hull needed to support the mass of the engine, base and propeller. Based on the density of aluminum (occupying the majority of the non-wooden aspects of the boat), the double hull should have roughly 3 times the volume of the engine block and base. This would keep the boat afloat. We have designed the hulls to be hollow, and stream line. One hull had enough volume to support the mass of the aluminum. Figure 3-20, Figure 3-22, Figure 3-24, Figure 3-26, and Figure 3-27 are the CAD and SolidWorks designs for the final boat.

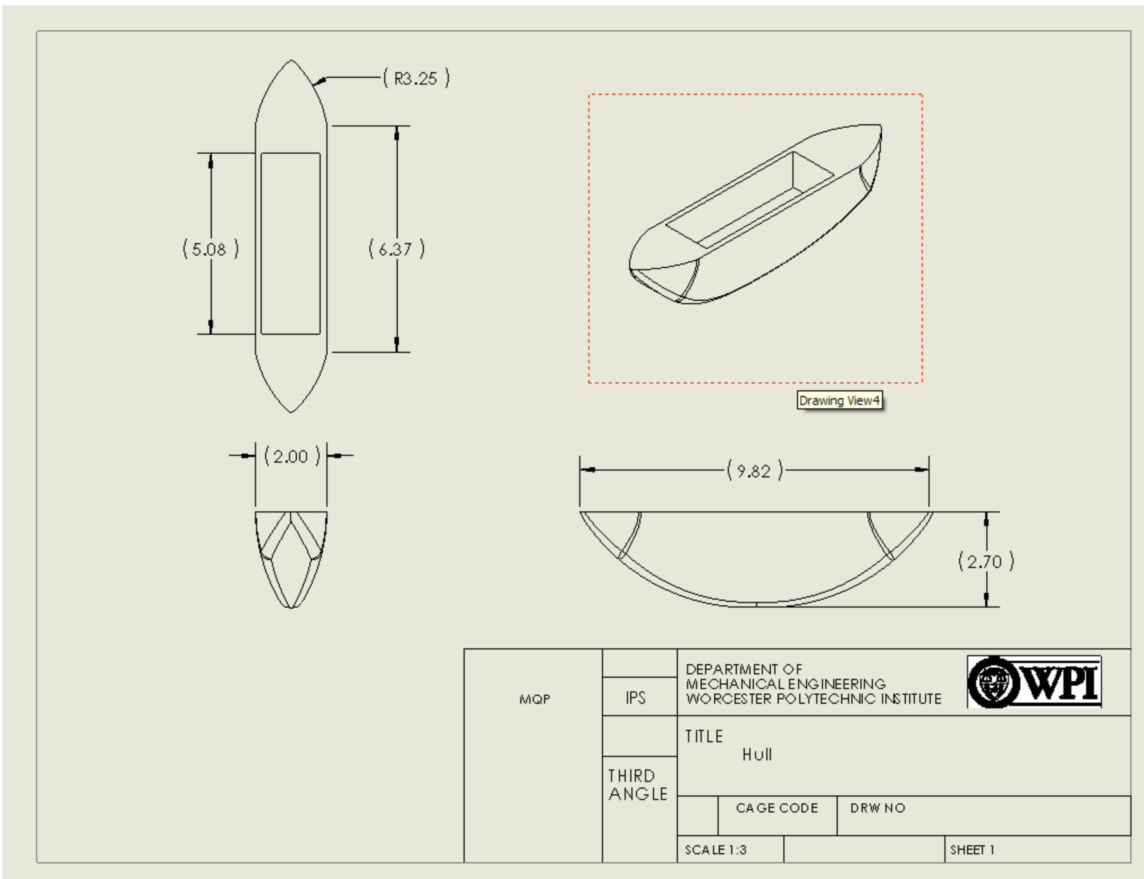

Figure 3-20 CAD Drawing of Hull

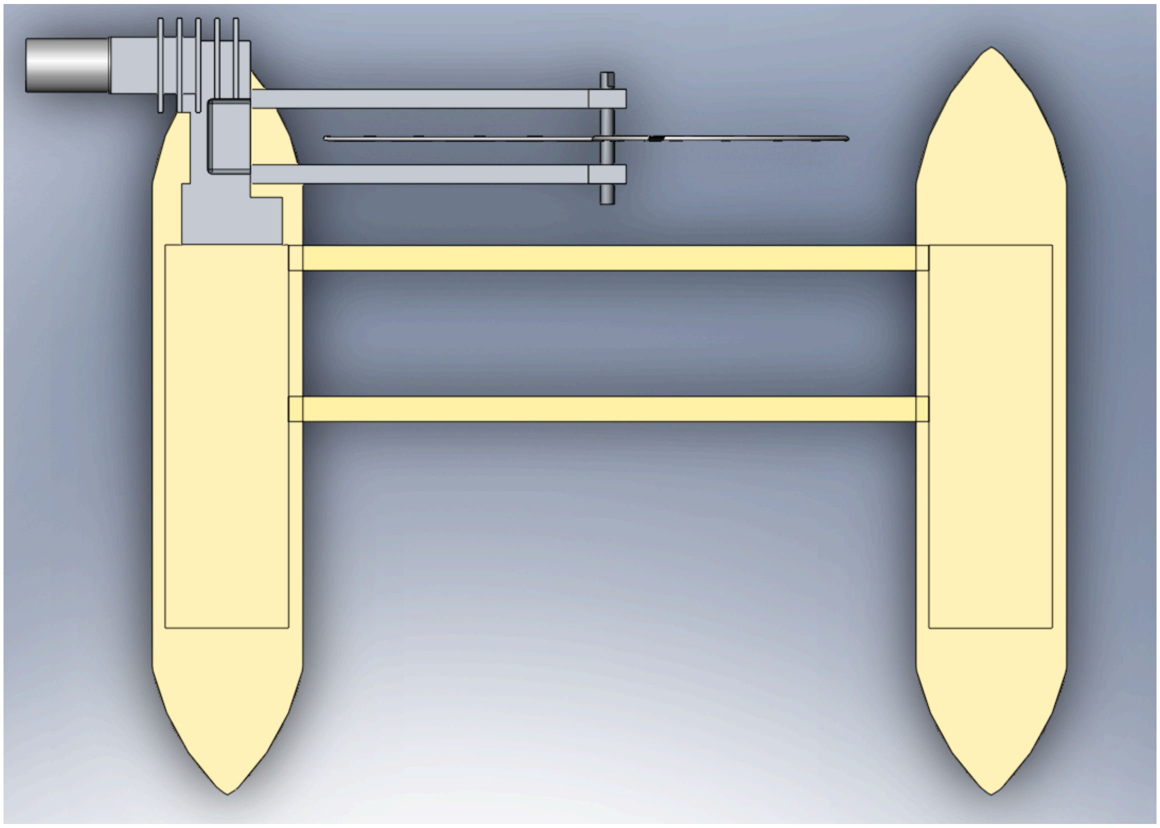

Figure 3-22 SolidWorks Model of Boat and Engine

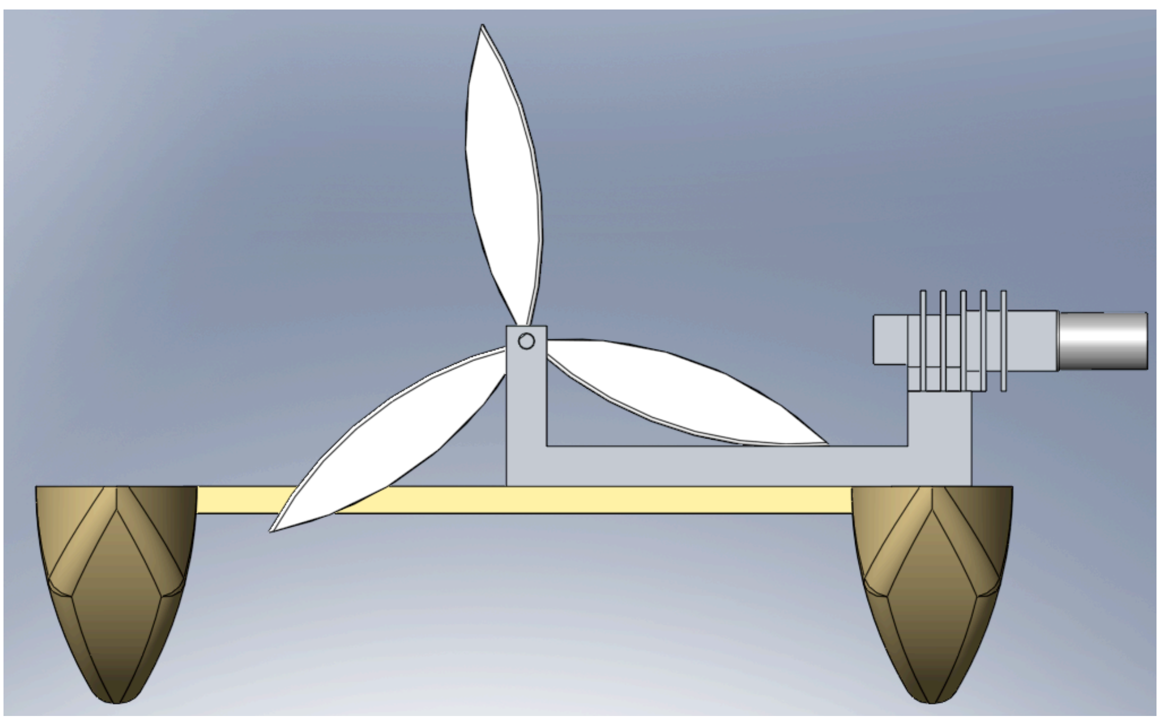

Figure 3-24 Front View in SolidWorks

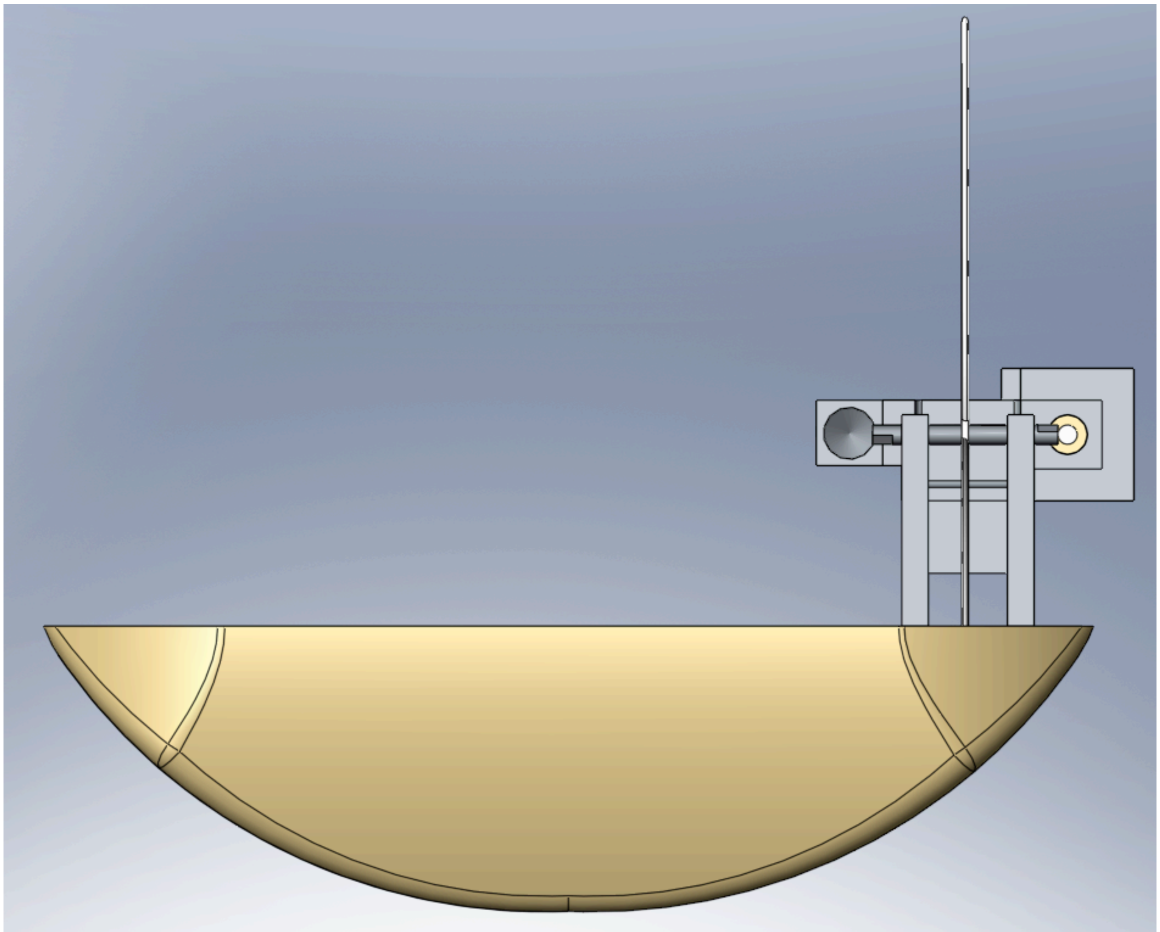

Figure 3-26 Side View in SolidWorks

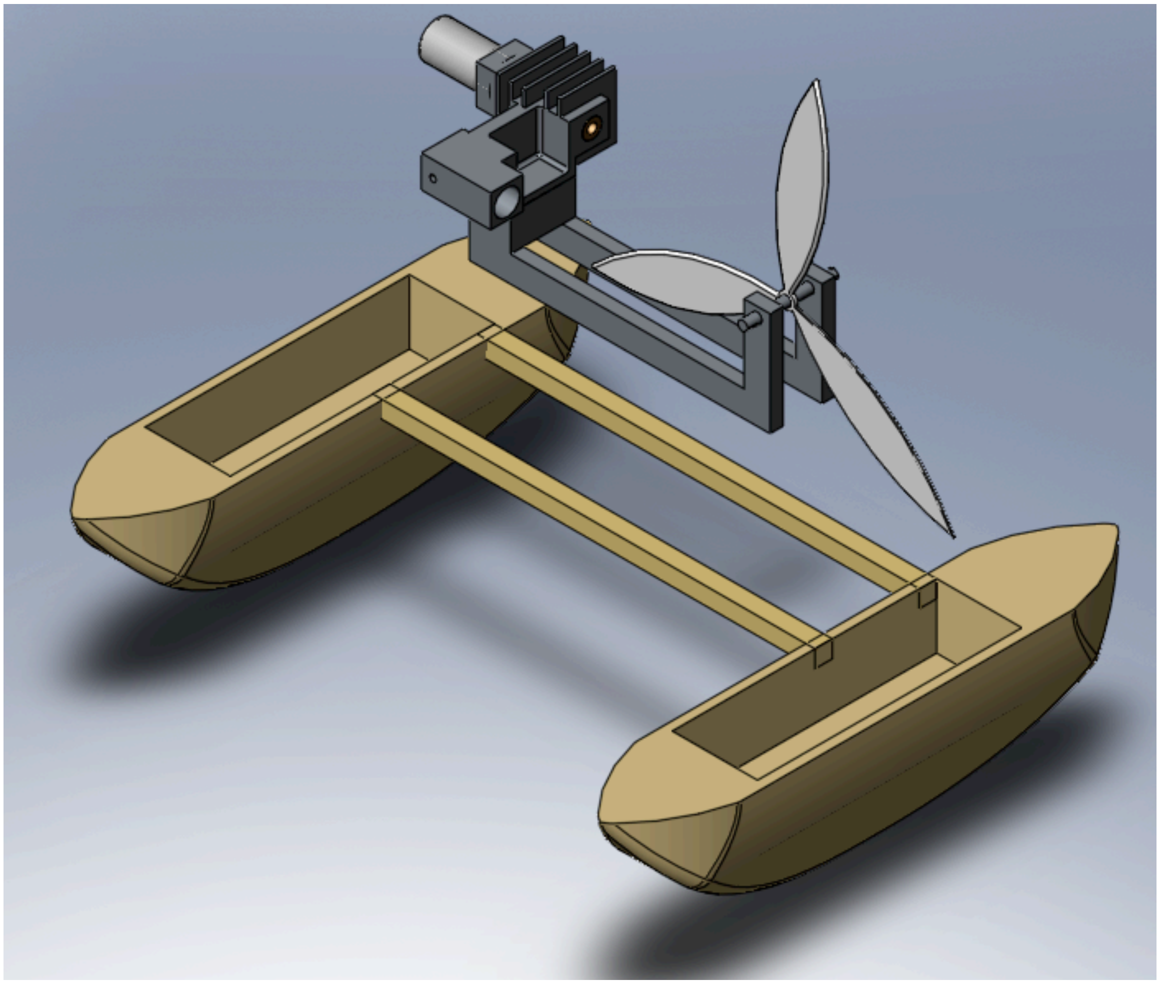

Figure 3-27 Final Proposed Design in SolidWorks

3.6 Propulsion

The amount of force required to propel the boat depends on the overall mass of the vessel and the amount of drag the boat creates through the water. One can calculate how much power is needed to move the boat at a constant speed. However, it is more important to calculate how much power is necessary to accelerate the boat to a certain speed from rest because this will require much more power. For this calculation we will need to consider the equation, F=ma. F is the force to propel the boat, m is the mass of the boat, and a is its acceleration. Not only do we need to consider the boat's mass but also its virtual mass. Virtual mass is the added mass created by traveling through a fluid. The virtual mass will be $m + k*m_{hydrodynamic}$. k is a coefficient which depends on the shape of the body traveling through the fluid. In the case of a circular cylinder, k = 1 (Milne-Thomson). $m_{hydrodynamic}$ is the mass of the displaced water. The equation will now be $F = m_{virtual}a$. For our design purposes, we desired to have a boat with a speed of .2 meter per sec and an acceleration of .1 meter squared per second. Once we had the force required to push the boat forward, we multiplied that number by the speed to acquire the power needed to move the boat. The virtual mass is extremely low because the mass of the displaced water is very low. The virtual mass can then be ignored. Because of the streamlined shape of the boat has a very low drag coefficient of 0.04 (Munson). The drag force will be modeled as $D_f = ½ \rho U^2 l b C_{df}$. The estimated required power for the boat will be 0.15 watts.

For propulsion we could use either a water propeller or an air fan. Both have advantages and disadvantages. The propeller will push water very effectively. However, if the blades on a propeller spin too fast they can lower the pressure surrounding the blades to a point where the water will cavitate. This not only decreases the amount of propulsion from the blades, but can also destroy and shear the blades off the propeller. In order to avoid this, gears would need to be fabricated to control the speed of the propeller. Designing a fan boat would not be as efficient as a water propeller. However, gears would not need to be fabricated to control the propeller speed. Because of this easier adaptability, we designed a fan boat.

Since there was no need for gearing, the flywheel itself can be the fan. Instead of turning a flywheel, the engine turns a fan. The engine was situated between the hulls so that the heating end is closer to one hull and the fan closer to the other hull.

3.6.1 Propellers

For this project we purchased 7 different model plane propellers of various sizes and pitches. All the propellers are made from light weight composites and range from 4 inches in diameter to 8 inches and diameter. The pitches range from 2.5 inches to 6 inches. We have also purchased 2 and three blade propellers. Depending on the power and rotational speed that the engine produces, various propellers will perform differently. When the angle of the propeller is great in reference to horizontal, the propeller is said to have high pitch. A high-pitch propeller can move the craft farther forward in one rotation than a low-pitch propeller. Also, a larger diameter propeller will produce greater thrust. Because of this, we decided to use the largest propeller so to give us the greatest thrust. We assumed there would be no performance loss using the heavier propeller because our flywheel spun at over 3,000 RPM during testing. The propeller is rated to supply enough thrust at 5,000 rpm to lift a model plane at similar weight as our boat (Figure 3-28).

Figure 3-28 Examples of Propellers

4 Results and Analysis

4.1.1 Fin Analysis

Our engine design contains a heat exchanger with 5 fins on each side. Based on Biber and Fijol's experiments we have designed the fins to be 1/16 of an inch thick with 3/16 of an inch spacing in between. The fins are ¼ of an inch tall. The following equations model the parameters of our fins for one face of the heat exchanger. For these calculations we are assuming complete transfer of heat from the blow torch (rated by manufacturer 1200 degrees Celsius) to the heating sleeve, and to the heat exchanger interior.

The most common design for fins is straight fin of uniform cross sectional design. Equations for this design are as follows (Incropera et al, 2007).

For the Temperature Distribution:

$$\theta / \theta b = \frac{\cosh m(L-x) + (h/mk)\sinh m(L-x)}{\cosh mL + (h/mk)\sinh mL}$$

$$m = \sqrt{hP/kAc}$$

$h \equiv heat\ transfer\ coefficient$

$P \equiv Perimeter$

$k \equiv Conductive\ coefficient$

$Ac \equiv Cross-\sec tional\ area$

$L \equiv Length$

For Free Convection Coefficient

$$Ra_l = \frac{g\beta(Ts - T_\infty)L^3}{\alpha\nu}$$

$$g = 9.8\frac{m}{s^2}$$

$$\beta = 6.789\times10^{-4}K^{-1}$$

$$Ts = 310K$$

$$T_\infty = 296K$$

$$\alpha = 22.5\times10^{-6}\frac{m^2}{s}$$

$$\nu = 15.89\times10^{-6}\frac{m^2}{s}$$

$$\Pr = .707$$

$$Ra_L = 66.71$$

$$Nu_L = \left\{0.825 + \frac{0.387Ra_L^{\frac{1}{6}}}{\left[1+(\frac{0.492}{\Pr})^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2$$

$$Nu_L = 2.192$$

$$h = \frac{Nu_L \bullet k}{L}$$

$$k = 26.3\times10^{-3}W/mK$$

$$h = 9.08\ W/m^2K$$

For Fin Heat Transfer Rate q_f:

$$q_f = M\frac{\sinh mL + (h/mk)\cosh mL}{\cosh mL + (h/mk)\sinh mL}$$

$$M = \sqrt{hPkAc\theta b}$$

$$\theta b = T_b - T_\infty$$

Fin Performance:

$$\varepsilon_f = \frac{q_f}{hAcb\theta b}$$

l = .00635

t = 0.001651

w = .03175

P = 2w + 2t

$P = 0.0668 \quad m$

$A_c = wt$

$A_c = 5.24 \times 10^{-5} \; m^2$

$k = 250 \frac{W}{mk}$

$m = 6.80 \, m^{-2}$

$M = 3.058$

$N = 5$

$Af = 4.57 \times 10^{-4}$

$\theta b = 1177 \; K$

$A_t = NA_f + A_b$

$A_b = 9.59 \times 10^{-4} \; m^2$

$A_t = 0.00324 \, m^2$

$Acb = 5.24 \times 10^{-4} \; m^2$

$q_f = 0.148 \, W$

$\varepsilon_f = .0265$

$n_f = \frac{\tanh mL_c}{mL_c}$

$L_c = L + (t/2)$

$L_c = 0.0072 \, m$

$n_f = .999$

$n_f = 99.9\%$

$$q_t = hA_t[1 - \frac{NA_f}{A_t}(1 - n_f)]\theta_b$$

$$q_{wo} = h(A_s)\theta_b$$

$$q_t = 34.6\,W$$

$$A_s = 9.59 \times 10^{-4}$$

$$q_{wo} = 10.25\,W$$

$$\Delta q = q_t - q_{wo}$$

$$\Delta q = 24.35W$$

$$\Delta q_{tot} = 97.4\,W$$

The fin design for the engine has a 99.9% efficiency and will perform roughly 97.4 watts more of energy than an engine without the fins.

After calculating the effectiveness for the fins, it is clear that the fins are not useful for our particular high heat design. Effectiveness should theoretically be 20% to warrant use (Incropera). So even though the fins are efficient, they are not useful. To increase the effectiveness the fins would need to be much longer. This would make machining the fins extremely hard. After consulting the machine shop managers about this design, we decided to forego the fins.

4.2 Engine Testing

The team used the makeshift dynamometer apparatus to test the manufactured Stirling engine and recorded values from both the tachometer and the mass balance during test runs. A total of 10 tests for each of the three different masses were completed. Averages for the 10 test runs of each mass are shown in Table 4-1 below.

Force (N)	Speed (m/min)	RPM	Torque	Power (W)
0.0785	90.8	567.50	0.00200	0.11879
0.0883	93.9	586.87	0.00225	0.13820
0.0981	104.6	653.74	0.00250	0.17105

Table 4-1 Average Values for Engine Testing

The team experimented with high and low masses/forces, but found that too little mass led to periods of non-contact with the tachometer and flywheel, and too much mass led to a complete stoppage of the flywheel. The data in the table shows three test masses including the lowest and highest values used in testing. The results from the testing showed that the team was able to manufacture a high speed, low torque engine which satisfied one team goal. The power results also showed that the engine would be able to supply enough power to force the boat into motion. From our original theoretical analysis, we needed roughly 0.15 watts of power to propel our boat at the speed of 0.2 meters per second. Again, the engine is being powered by a blow torch and the power the engine produces is a maximum. The heat input is roughly 1300 degrees Celsius. Since the energy input is very high and the output is low, the efficiency of the engine is low.

4.3 Engine Boat Setup

After the group tested the engine, the engine was mounted to the base with extended arms intended for the boat application. However, after assembling this setup there was a problem. Upon heating the engine, the crankshaft did not turn. Even though the engine had previously worked with the base with shorter arms, it was not working now. The group inspected the engine and played around with the phase change arrangement. However, the group could not find an exact problem. There seems to be a problem in the alignment of the pistons to the end of the crankshaft. This is causing more friction at the apex of the phase change than was experienced with the smaller setup. Even though this friction causes only slightly more force to be needed, it is assumed that this extra force is higher than the output of the engine. Another problem the group noticed was with the seal made by the power piston. The tolerance could be tighter which would increase performance.

Theoretically the design should work. No extra power should be needed with the extended arms because no more work is being performed than the smaller arrangement. However, problems with alignment become exaggerated. Because the engine has low torque, it cannot overcome the added force.

Through our tests, we discovered that when no force is applied to the flywheel, the engine turns at 3,000 RPM. If the propeller were to spin even at a third of this speed it would still create sufficient thrust to propel the boat forward based on the manufacturer's ratings for the propeller.

4.4 Final Assembly

The boat was successfully constructed and with the exception of the engine in configuration with the extended arms, the design works as planned (Figure 4-1, Figure 4-2, and Figure 4-3). The boat has a low drag profile, is light in weight, and is well balanced when floating in water. The controls for the boat also work.

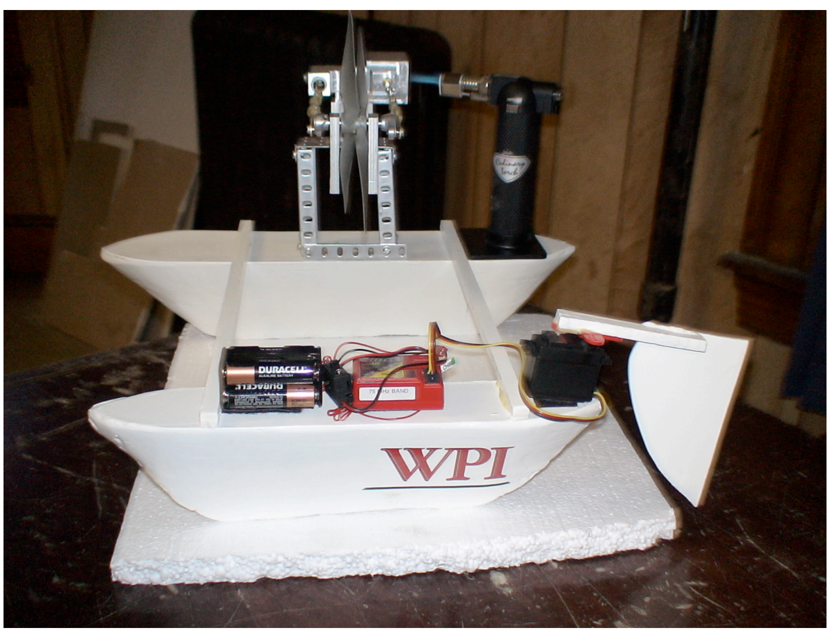

Figure 4-1 Final Boat with Rudder Attached

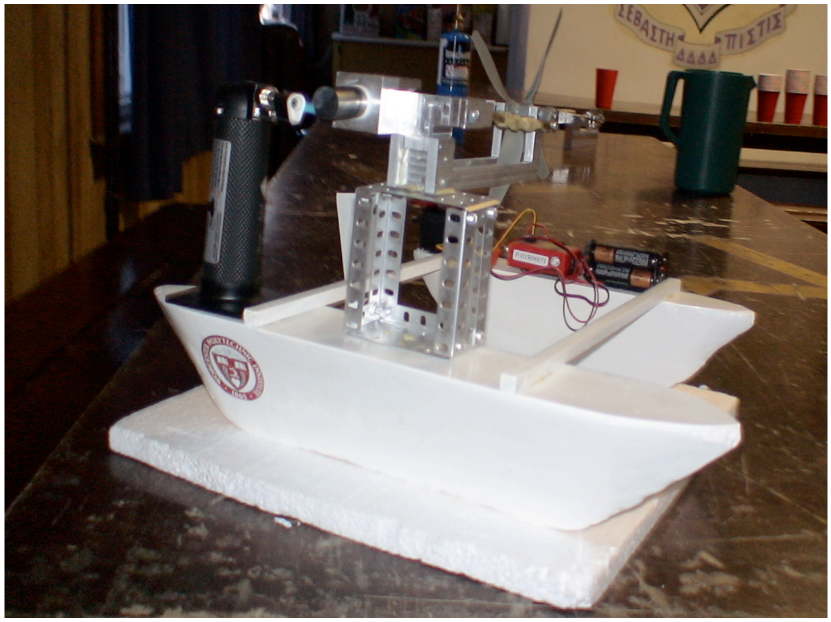

Figure 4-2 Final Boat with Working Torch

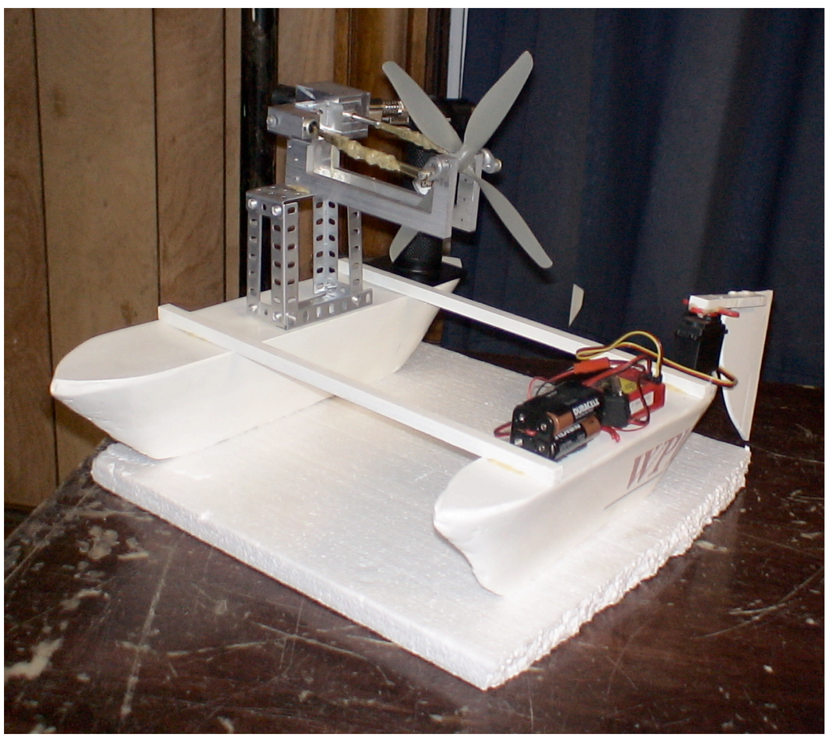

Figure 4-3 Isometric View of Final Boat

5 Conclusions and Recommendations

Based on the work outlined above, the team concluded that a working Stirling engine for a model boat based on CAD designs could be manufactured. The team's work during the design phase proved to be a successful approach for the machining and assembly stage. Part of the original design made use of fins for the engine. However, no fins were included in the final design due to their low fin effectiveness. The fin efficiency was calculated to be around 2% meaning that the team would have to enlarge the fins by about 50%, and consequently, enlarge the engine proportionally. This idea was not feasible in the given timeframe, so the group decided to scrap the fins for the final design.

Overall, the engine did produce an average maximum engine power output of 0.171 watts. This would be more than enough power to put the boat into motion even using conservative values in the boat design calculations. However, the final resulting Stirling engine powered model boat was unable to function properly due to multiple reasons. The group believed that there was a leak at some point in the regenerative cycle which caused the engine to lose a significant amount of power. Also, the brass linkages that the group used for the engine were not perfectly aligned due to the fact that they were not machined. Rather, the team combined two shorter linkages in an effort to simulate a machined linkage. This effort resulted in a point in the rotation of the flywheel where the linkages locked up and became static. The team altered the phase change of the linkages, but could not find an angle that would work.

As a result of the problems with the engine, the team recommended that future work be completed including an analysis of the engine to discover the exact points where leakage occurred. The group also felt that designing and machining brass linkages would allow the engine to function properly without reaching a static point. The team did conservative analysis for the boat design to determine how much power would be needed, but further analysis could be completed for the desired engine size based on precise boat velocity and engine based specifications. The team also had the opportunity to discuss the project with an employee of the DEKA Company who works with Stirling engines on a much larger scale. Further conversations with this company about their refinements used with Stirling engines would prove invaluable in solving the problems experienced with this project.

6 Works Cited

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