ENPH 454 Advanced Engineering Physics Design Project-Final Report

Solar Powered Water Pump

Date of submission: Dec 5, 2021

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Submitted December 5, 2021

Abstract

There are many underdeveloped communities experiencing water scarcity that would benefit from a low cost and reliable pumping system. This project proposes a solar powered Stirling engine water pump to transport water from nearby surface water sources to these communities. This report describes a 1/50th scale prototype consisting of a gamma Stirling engine, Fresnel lens and centrifugal water pump. Materials were selected to minimize costs. The lens and centrifugal pump met design objectives, however, problems with the displacer and working piston prevented the integrated system from functioning properly.

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1. Introduction

Water scarcity is experienced by many communities globally resulting in long hours spent fetching water, disease, and severe dehydration. Despite aid from outside organizations, low-cost reliable solutions are still necessary.

1.1 Motivation

In Mozambique, women spend up to 4 hours a day collecting water as only half the country's clean surface water sources are operational [1]. Less than 50% of the population of Mozambique has access to drinking water for more than 7 hours a day. Increasing access to safe water for drinking and hygiene improves the health, safety, education rates, and economy of a community [2]. This project aims to design a low-cost and reliable surface water pump for use in underdeveloped areas to increase access to clean water. The main stakeholders are individuals experiencing water scarcity, the government of Mozambique and Non-government organisations.

1.2 Background

Since 1998, outside organisations including the World Bank and the United Nations (UN) have been working with the Government of Mozambique to provide consistent access to drinking water to 60% of the nation's population [3]. However, it is suspected that corruption and diversion of funds has prevented this goal from being achieved [4]. The nation has been working with non-government organizations (NGO) to provide communities with wells and filtration systems [5].

Current solutions include hand-pumped shallow wells, electrical pumps powered by diesel generators or solar panels [1], [6], [7]. These pumping systems have significantly improved rural communities' access to safe drinking water but rely heavily on external support [8]. Existing solutions have high servicing costs and lack reliability resulting in dozens of them being abandoned yearly [8]. Wind powered mechanical pumping systems have proven successful, however, these systems tend to have a low head [1]. NGOs continue to look for low-cost, reliable, and sustainable pumping systems.

1.2.1 Stirling Engine

Stirling engines are a sustainable power source that can be used to drive mechanical or electrical pumps. Stirling engines extract energy from the expansion and contraction of a working fluid during heating and cooling. The ideal Stirling cycle is modelled in Figure 1. The working fluid is compressed isothermally using heat transfer to the surroundings before being heated isochorically. The working fluid then expands isothermally and is cooled isochorically.

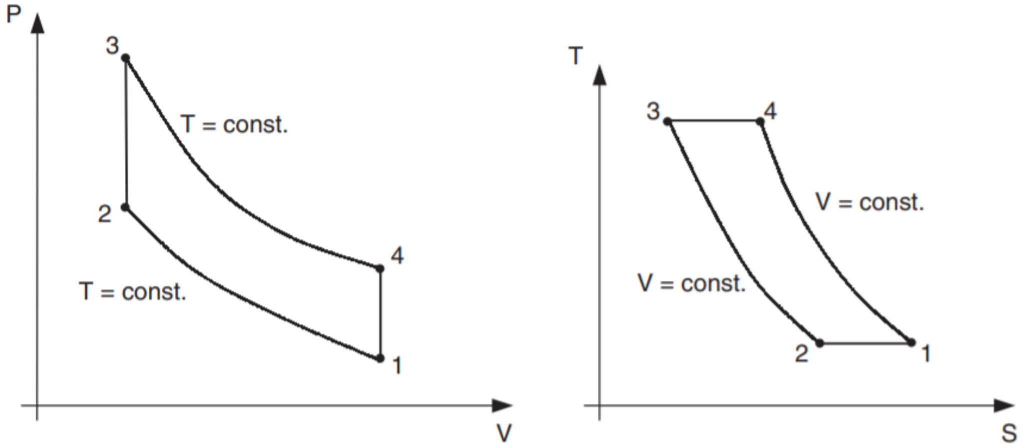


Figure 1: Pressure volume plots and Temperature entropy plots of the ideal Stirling Cycle. The figure was re-drawn based on Figure 1 in ref. [9]. (Editorial note: please see ref. [9] for the correct representation of the T-S plot, as it may have been modelled inaccurately)

The use of solar powered Stirling engines for water pumping has been investigated in rural India, however, this technology has never been attempted in Mozambique [9].

1.2.2 Water Pump

The considerations for pump design include head, volumetric flow rate, power source, and priming. Centrifugal pumps use impellers to push water through the system and have efficiencies upwards of 80% [10]. Centrifugal pumps are the most common form of electrical pump, however, they are not effective for use in hand pumps [11]. Traditional hand pumps use suction to transport water, are self priming, and are easy to construct and maintain[1]. However, these pumps cannot provide a large head or volumetric flow rate.

The use of fluidic pumps may be best suited to regions with limited infrastructure due to their lack of moving parts. These novel designs are highly inefficient with limited head production and have yet to be employed on an industrial scale [12].

1.2.3 Heating source

Solar thermal collection technology can be used to heat the working fluid in a Stirling engine. Thermal energy can be collected by parabolic troughs, heliostat fields, linear Fresnel reflectors, parabolic dishes, compound parabolic concentrators and linear Fresnel lenses [13]. Parabolic trough plants have been implemented on an industrial scale in California, Nevada, and Spain [9]. The reflectors follow the sun using solar trackers and heat molten salt to 150-350 degrees Celsius.

1.3 Project Scope and Goals

The goals of the full-scale pumping system are to pump water over 3 km distance and 3 m of elevation at a flow rate of 24000 L/day. A distance of 3 km was selected because the average distance between homes and water sources in sub–Saharan Africa is 1.4 km [14]. Assuming a normal distribution, 97.8% of the population will be serviced with a pumping distance of 3 km [14]. Mozambique is relatively flat, and we are focusing on surface water, therefore, a 3 m head was selected as a design objective. In regions with greater elevation change or distances pumps can be implemented in series. A flow rate of 24000 L/day was chosen to meet the basic drinking and hygienic water needs of a 500 person community [1].

A 1/50th scale prototype was designed and built to allow for safe testing and feasible manufacturing.

Our project was constrained by the resources available in the region of interest. We are focusing on underdeveloped regions; therefore, cost was minimized. The project focuses on remote areas, so parts were designed to be simple and reliable. Reliability ensures parts do not break often, and simplicity ensures that parts can be repaired and replaced locally which minimizes reliance on external aid.

2. Design Decisions

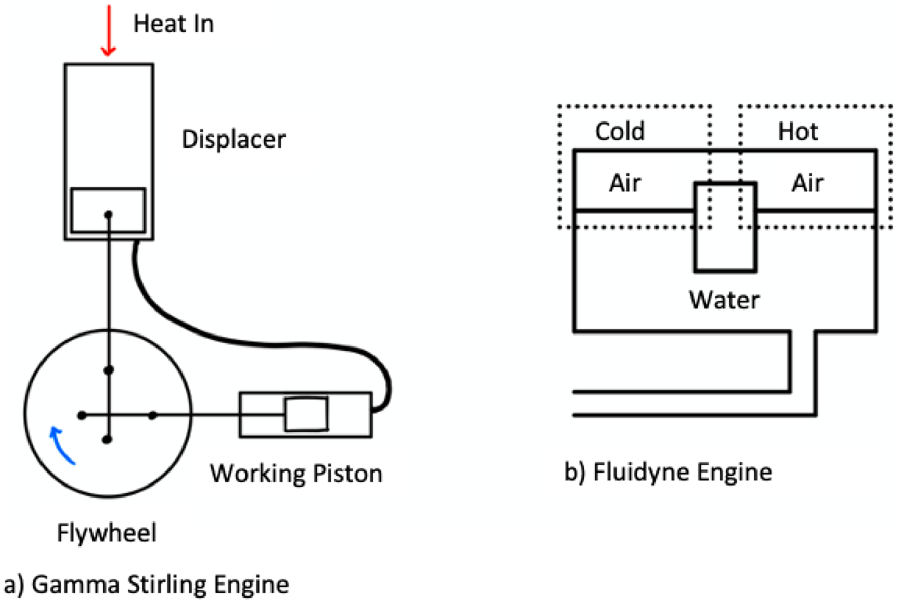
The goals for the prototype were to provide a head of 0.5 m, a volumetric flow rate of 1 L/minute at a temperature difference of 100 C, and an engine rotational speed of 180 rpm.

2.1 Engine

We used a Stirling engine as the power source because they are simple compared to other renewable energy sources and the group was interested in the technology. We considered many types of Stirling engines, but we focused on gamma Stirling engines and fluidyne engines (shown in Figure 2) because of their simplicity.

The gamma Stirling engine has 3 main components: a displacer, a working piston, and a flywheel. The displacer moves the working gas between hot and cold sections. The fluctuations in working gas temperature cause the gas to expand and contract which drives the working piston, moving the flywheel. The flywheel maintains momentum between power strokes. A 90-degree offset between the displacer and piston crank arms controls system timing.

Fluidyne engines integrate the pumping and power generation subsystems. Air is heated and cooled causing it to expand and contract which displaces water. One-way valves allow for a consistent direction of flow. Although they are more complicated than Fluidyne engines, we chose to build a gamma Stirling engine because they are four times more efficient [8].



a) Gamma Stirling Engine

b) Fluidyne Engine

Figure 2: a) shows a schematic of a gamma Stirling engine and b) shows a fluidyne engine.

2. 2 Pump

An off the shelf mechanical pump was purchased to minimize costs and construction time. Gamma Stirling engines include a flywheel and axel therefore, a centrifugal pump can be easily incorporated onto the axel. The head of a drill was used to attach the pump for easy assembly and disassembly when necessary.

2. 3 Heating

Stirling engines are powered by a temperature difference generated by an external heat source. One possible design consists of an array of aluminum or copper fins in a light absorbent box, as shown in Figure 3B. The fins would heat the working fluid and propel the fluid through the system by convection. The second design consists of parabolic reflectors that focus light onto copper pipes containing the working fluid as shown in Figure 3A. Ideally, alcohol would be used as the working fluid because of its low evaporation temperature. Convection, condensation, and evaporation would propel the fluid through the system.

This diagram includes images that could be copyrighted.

Figure 3: Early heater designs with the solar heating system with air as the working fluid from [13] shown in b and parabolic trough heating array diagram in a from [14].

These designs are large, complex and can add dead volume to the system. A more direct approach is to incorporate a Fresnel lens to focus solar light on the hot end of the displacer to heat the working fluid. Figure 4 illustrates a Fresnel lens and shows how it works like a conventional lens. The lens is scalable to a full-size system and can heat the hot end of the displacer to 300 ^{0}C [13]. In this design, the constraint is the ratio between the size of the lens and focal point. For a large-scale design, systems like the parabolic reflector combined with a Fresnel lens can be employed to reach higher temperatures [13].

This diagram includes images that could be copyrighted.

Figure 4: Image of a Fresnel lens compared to traditional lens, image from [16].

Modelling the 1/50th scale system using the Resistive network technique indicates that the system would require 13.4 W of power to operate. The hot end of the displacer is 32.8 cm^2, therefore, assuming an average efficiency of 75%, the lens must be at least 172 cm^2 [13].

3. Safety, Environmental Concerns, Ethical Concerns, Equity

Environmental concerns were at the core of our design as we were focused on powering our system sustainably. The solar concentrator could start a fire, this risk will be mitigated by clearing the area around the pump of vegetation.

Safety risks include the grease in the system contaminating the pumped water, however, this is unlikely because the engine and pump sub systems are kept separate. Leaching of harmful materials from the tubing is a risk however, this has been mitigated by using pipes designed for water transport. Testing should be performed in Mozambique to ensure the elevated temperatures and weather conditions do not degrade the pump or tubing.

Safety risks during testing include heat and moving parts. The end cap of the displacer was heated to 170^0 C. The risk of burns was mitigated by wearing gloves, long pants, and closed toe shoes. Additionally, the heat gun was always held in place to prevent it from falling and hurting someone. The vicinity of the experiment was kept clear of passersby. The risk of moving parts injuring someone was mitigated by ensuring low operating speeds. A cart was used to carry heavy parts to prevent injuries.

Accessibility to individuals with limited education and resources was a main ethical concern. Therefore, the engine was made from readily accessible materials and was designed to make repairs and installation easy.

4. Methodology

The following section outlines the steps taken to construct and iterate the design.

4. 1 Heating

The optimal angle for solar panel tilt is equal to the geographical latitude [15]. Mozambique is below the equator, therefore, the Fresnel lens should face true north at 18.67 degrees from the ground. Good quality Fresnel lenses can be quite expensive, so we used a Fresnel lens from an old Elmo projector.

A support for the lens was built out of wood. For testing in Kingston Ontario, the lens was placed at 38 degrees as shown in Figure 5.

Figure 5: Support for Fresnel lens.

4.2 Base and supports

The support structure was made from five distinct components which include the base plate and supports for the displacer, piston, flywheel and pump. The supports were designed to prevent undesired motion of the components to prevent energy losses. A factor of safety of 5 was selected because of the long timescale of the project and its importance to the local community [16].

The piston and displacer supports were constructed from aluminum. Initially, the components were placed in a trough on the top of the supports. The components were then held down by a zip tie or metal strap. With the addition of double-sided tape on the supports, this design worked well for the displacer, but the piston was able to slide during operations. New piston supports were designed with a hole for the piston ends which was then secured by a nut. This design was successful in its ability to support the piston and prevent it from sliding.

The flywheel and axle supports were designed for a low rotational rate of 900 rpm based on a rotational factor of safety of 5 on the desired rate of 180 rpm. Low speed ball bearings, capable of supporting 1000 N, were used to allow for the smooth rotation of the flywheel with the drive shaft. The bearings were affixed to two aluminum supports which also had a maximum load of 1000 N. This design worked well and allowed free rotation of the flywheel.

The pump support system was constructed using wood, with the pump affixed to the support plate using screws. This design used four bolts to attach the pump to the wood frame to prevent the pump from rotating with the drive shaft. This design was successful in supporting and securing the pump.

The supports were attached to an aluminum base plate such that the piston and displacer were able to move through the correct range of motion. During testing it was found that the plate flexed which led to significant losses, therefore, it was reinforced using wood beams.

4.3 Displacer

The displacer was designed to have a swept volume of 4 inches and a length of 13.5 inches based on another gamma Stirling engine design [17]. The ratios between working piston swept volume, displacer swept volume and displacer length were scaled to meet the pump's energy requirements. Initially, the displacer was simply a foam cylinder 12 inches long and 1.7 inches in diameter. The displacer rod was attached with gorilla glue, however the rod moved out of alignment during operation and then detached during testing.

The tilting was eliminated by adding 1.9-inch diameter 3D printed end caps to the foam displacer. The increased diameter allowed the displacer to slide with minimal resistance but did not allow the displacer to tilt within its housing. The end caps and foam core were attached using a threaded plastic rod. The connection between the displacer and rod was improved by screwing the rod into the end cap.

After the initial break in the displacer, it was decided the displacer housing should be modified to allow for easy repairs. An ABS coupling was added to allow access to the displacer without destroying the displacer housing. To improve heat absorption the heated end cap was painted black.

4.4 Axel and flywheel

The drive shaft was designed to allow for the maximum swept volume of the displacer and piston to be reached. The displacer crank arm was attached to the end of the axel. The displacer arm was constructed using a 2.5-inch-long thin aluminum plate and a locking washer. This design was selected because of its simplicity and the displacer's low torque requirements. The piston arm was welded to the shaft between the flywheel and pump. The arm was 2.5 inches long to pull the piston through its required range of motion. The two crank arms were offset by 90 degrees.

5. Final Design

The final design can be seen in Figure 6. The entire system is attached to an aluminum sheet reinforced on the bottom by 3 wood beams to prevent flexing. The axel, displacer and piston supports are aluminium. The working piston is screwed into its supports. The axel passes through its supports using bearings to allow it to rotate. The displacer housing rests on troughs in its supports and is attached using double sided tape and zip ties that pass over the displacer and through a hole in the support.

The displacer is composed of foam with threaded plastic passing through it which is attached to plastic end caps. The displacer rod is screwed into a plastic end cap. The displacer housing consists of ABS pipe with a screw on coupler to allow for repairs. The aluminium heated end cap is painted black. The other aluminum end cap has an NPT fitting which attaches to the working piston using flexible tubing and a hole with an O-ring seal to allow the displacer rod to move. The displacer rod attaches to the axel using a simple pin joint and a y pin joint.

The working piston attaches to the axel using a crank shaft and a y pin joint. The flywheel attaches to the axel using a set screw. The pump is screwed on to the threaded end of the axel and is held in place by a wooden support.

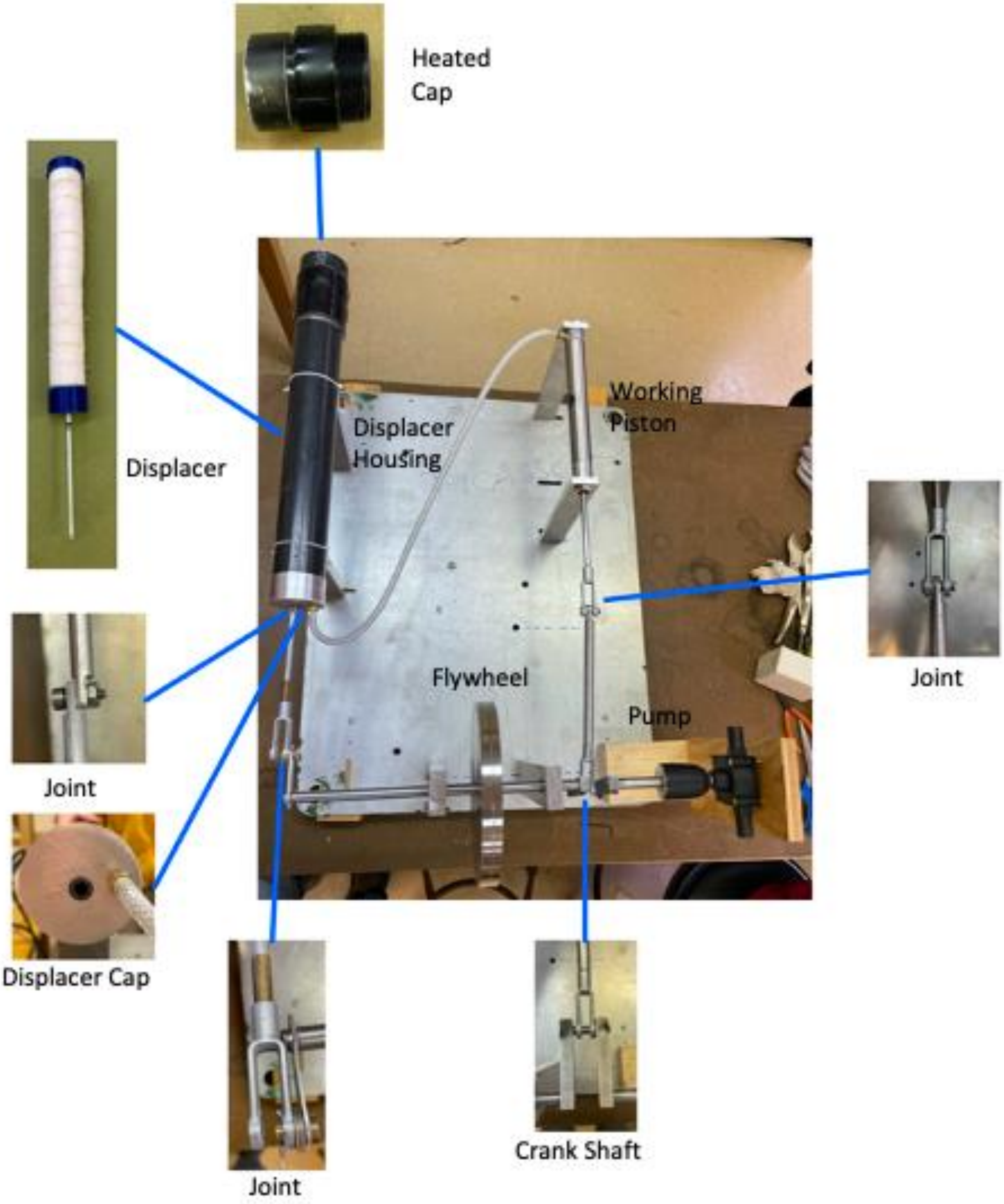


Figure 6: The final design the sub-components shown in sub-images.

6. Testing, Validation, and Iteration

The final engine system did not function as designed. To determine the cause of this issue, each subsystem was tested and iterated.

6.1 Integrated system heating

The system was heated using a heat gun to simulate the effects of the Fresnel lens. An infrared thermometer was used to measure the heat from the blackened hot end of the system, and a thermocouple was used to measure the temperature on the cold side of the displacer. The system was heated to determine at what temperature the system would start to rotate. The temperature is plotted as a function of time in Figure 7.

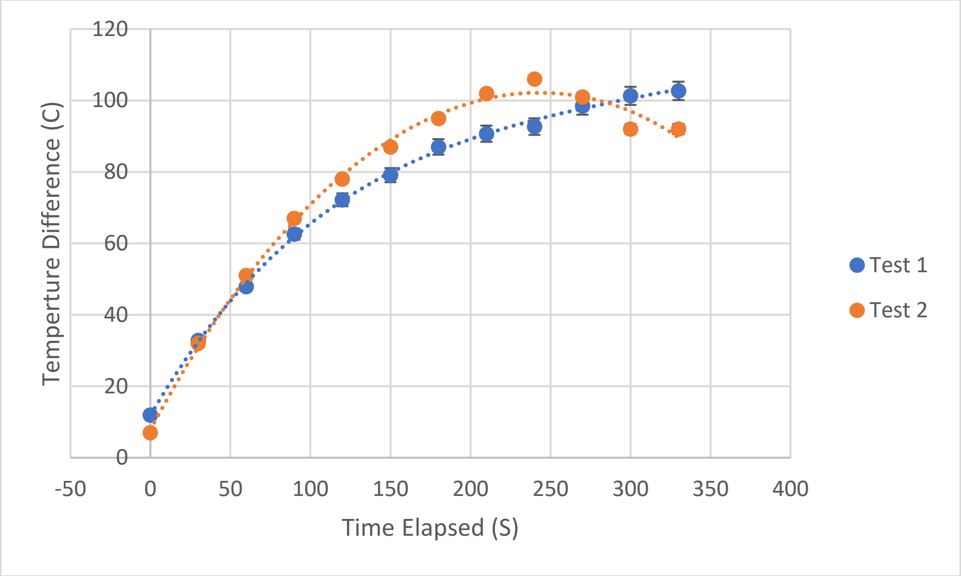


Figure 7: Plot of the first two heated trials with the entire system connected with error bars of ±1 degree and ± 2 seconds.

Our initial testing that the engine could not rotate independently at the design temperature. To improve the design, the system was analysed for points which would have the highest losses. After testing the components and accounting for losses the required temperature difference was determined to be 160 Kelvin. The temperature vs time test was repeated with a maximum temperature of 170 C at the hot end. The plot of the temperature difference of the second test in shown in Figure 8.

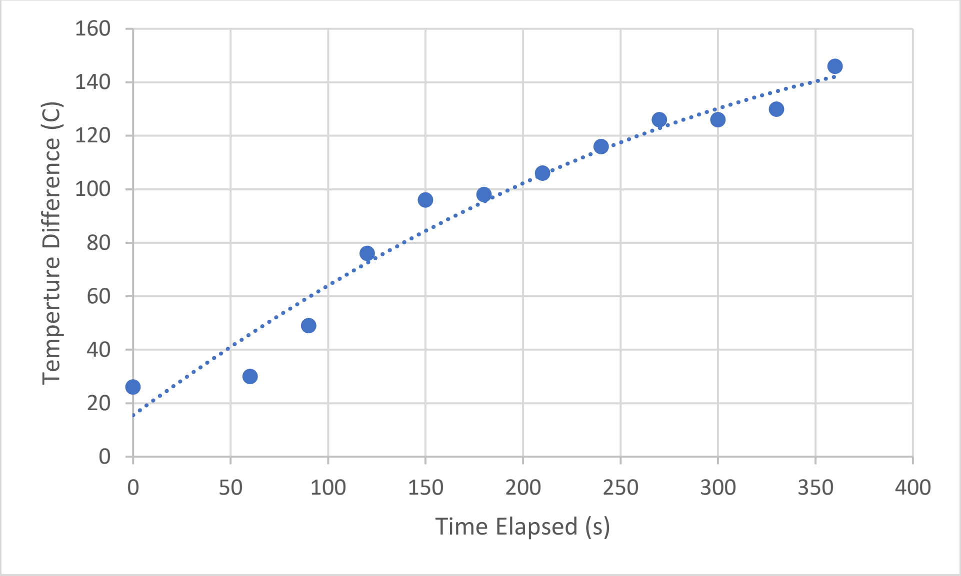


Figure 8: Plot of the first two heated trials with the entire system connected with error bars of ±1 degree and ± 2 seconds.

The test was ceased after 6 minutes following the structural failure of the coupler on the displacer caused by excess heating.

6.2 System Force Requirements

The forces required to move the different components were measured using a Newton meter. Initial testing revealed large losses in the displacer and working piston seals, therefore, both components were greased which yielded significant reductions in friction. The greased displacer was found to require a force of 0.3 +/- 1 N to drive it. The greased piston was found to require a force of 8.6 +/- 1 N. The flywheel required a torque of 11.6 +/- 1 N.

6.3 Heating source

The concentration of the lens was tested using an optical power meter and a single lightbulb. The optical power was measured at the focal point of the lens with and without the lens in place as shown in Appendix C. The power measured without the lens was approximately 3.1 milliwatts. With the lens, the power was amplified over 600x to 2.03 watts, as shown in Appendix C.

The Fresnel lens was mapped to ensure the light was properly concentrated at the focal point. The optical power output was measured at various positions beneath the lens, as shown in Figure 9A. The light was approximately 25x stronger near the center than the edges, as shown in Figure 9B, indicating proper concentration.

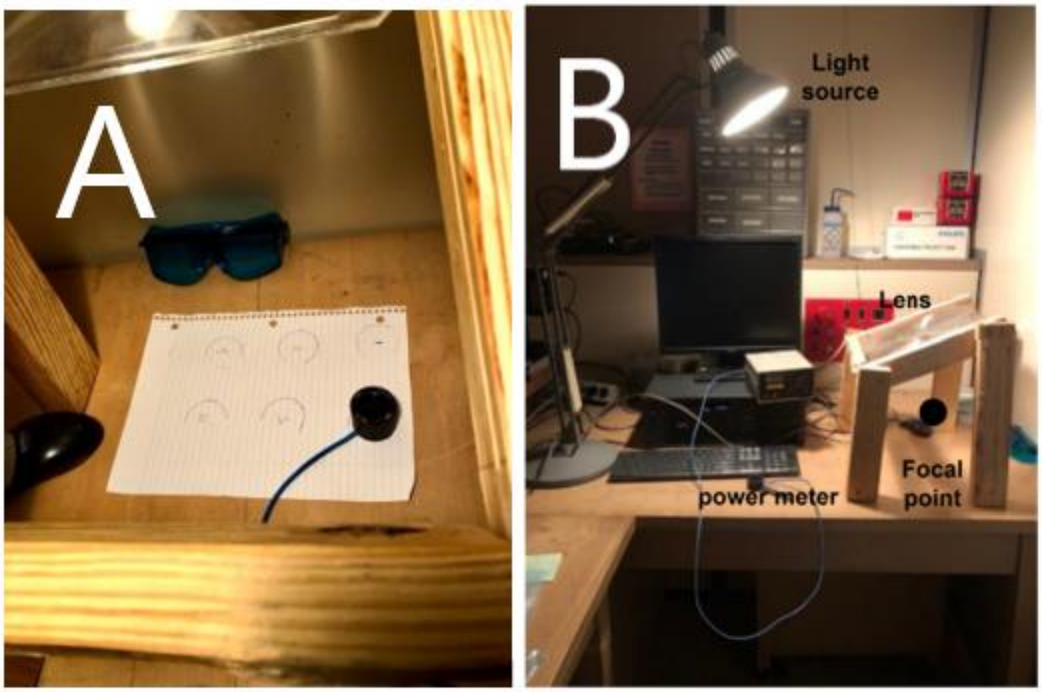


Figure 9: image A shows the position test used for mapping of the Fresnel lens, and image B shows the overall testing setup used for testing the lens power from an incandescent light bulb.

6.4 Pump

The pump was required to move water at 1 L/minute at a head of 0.5 meters. The rotations per minute (rpm) necessary to achieve this goal were measured. Figure 10 shows the experimental set up. The pump was driven by a drill. A small piece of tape was put on the drill to visually count the rotations. The pump was filmed while filling a 200ml beaker after which the rotations were counted and divided by the fill time. The flow rate as a function of rpm in shown in Figure 11. 180 rpm was found to provide a head of 0.57 m and a flow rate of 1 L/minute.

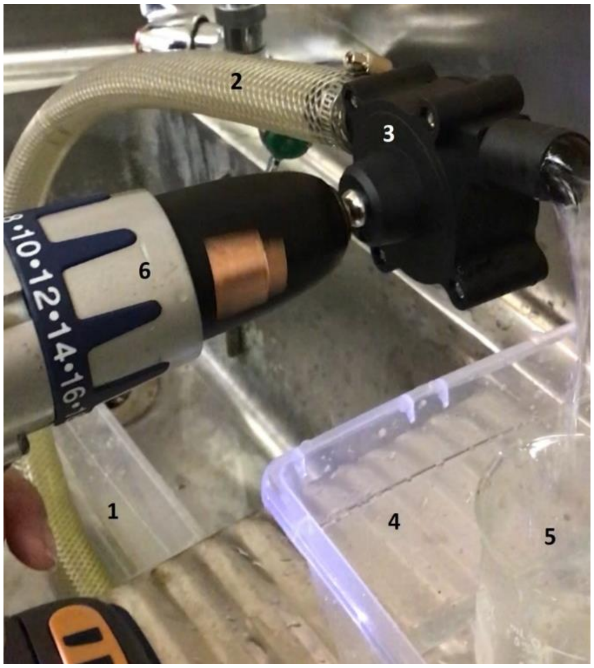


Figure 10: Image from testing the pump flowrate to rotations per minute with the source water (1), connected to the pump (3) by the piping (2), which is 0.57 meters above the source. The pump is powered by the drill (6), and the flow rate is measured by taking the time to fill a 250 ml beaker (5), with a safety bucket around the beaker (4).

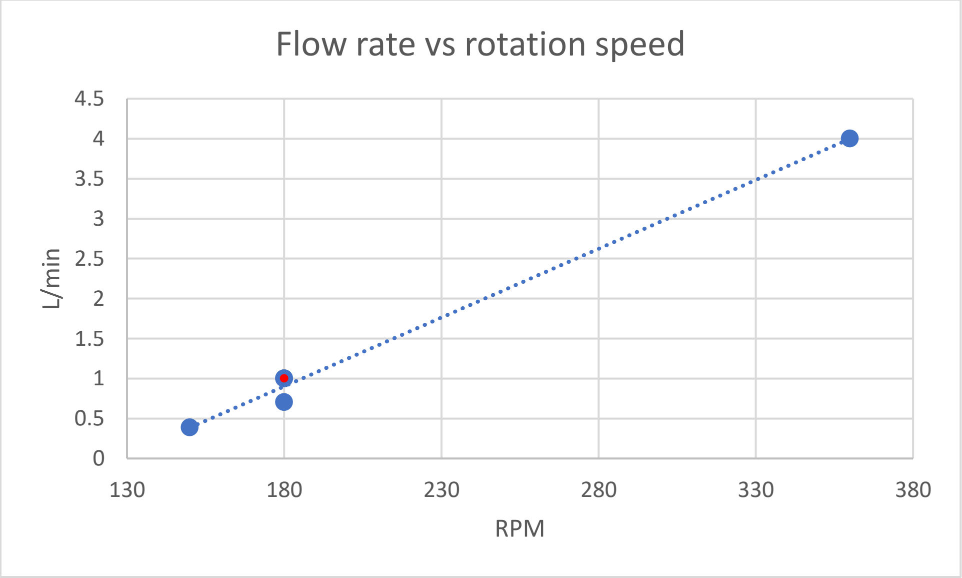


Figure 11: RPM measured at various flow rates. The desired flow rate of 1 L/min is shown in red.

7. Discussion

The prototype displayed several key aspects of our desired design. However, the final system did not operate successfully. The failure of the ABS coupler occurred 70^0 C below the listed failure temperature which prevented testing at higher temperature. Several components of the design show potential for implementation into further Stirling engine designs for water pumps.

The use of a Fresnel lens as a heat source was demonstrated to provide the energy concentration required to drive the Stirling engine at its design parameters. The cost of Fresnel lens systems makes them appealing for applications in the developing world. Their rugged design is desirable for long term use under harsh conditions.

The centrifugal pump attached to the Stirling engine was a novel design idea that could be implemented in other systems. The design could be improved by using a pump with lower torque requirements. A gearing or pulley system could be used to manually adjust the rotational speed of the pump. This type of modification could prevent over pumping.

The Stirling engine might benefit from the use of a working fluid other than air. Other working fluids have been investigated under lab settings [18]. These pumps may be able to provide a higher-pressure difference at lower temperatures which would allow for the system to overcome the resistive forces in the piston.

8. Economic Analysis

The 1/50th scale model of the system is costed at $481.73 to construct as outlined in Appendix B, Table 1. However, the cost of the system is not directly scalable to a full-scale model. To build a full-scale pump, 50 times the energy would be required, demanding the use of a modified Fresnel heading system. These heating systems cost $234/m^2 of concentrated light [13]. To heat the hot end of the displacer to 300 C, the heating system would need to be approximately 0.86 m^2, costing $201.24.

To achieve a flow rate of 50 L/min and a head of 3 meters costs approximately $750 [1]. The Stirling engine cost is almost directly scalable resulting in a total engine cost of approximately $17 081.50. Full scale total system cost would be $18 032.74 [6]. Its important to note that these costs do not consider increased losses from different pipe diameters, and other scaling challenges.

Solar power pumps which the world bank has employed in Tasmania with similar outputs cost around $67 200 before installation. The Stirling pump is an attractive alternative at approximately a third [16],[17].

9. Conclusion

Although the stirling pump failed during testing, many imporant lessons were learned and principles demonstrated to inidcate that a stirling powered water pump is a viable solution for implemntation in the developing world. The design demonstrated that a Frensel lens can be used to produce the required temperature difference in Mozambique. The design shows that a centriful pump is suitable for implementation with a Stirling engine. Work is still required to demonstrate that the stirling engine design can function as required. Future work should focus on the implementation of low cost, and low temperture difference Stirling engines. It is recommended to work with high insulating materials with high melting points to prevent failure from excessive heat. Trials inidicated that the primary reason for the engine's failure was the high force required to move the piston, highlighting the importance of a low friction system. It is possible that the use of a working fluid that evaporates in the displacer and condenses in the working piston would improve the design performance and meet the project design goals.

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Appendix A – Technical Deign Drawings

All appendices combined have a page limit of 15 pages.

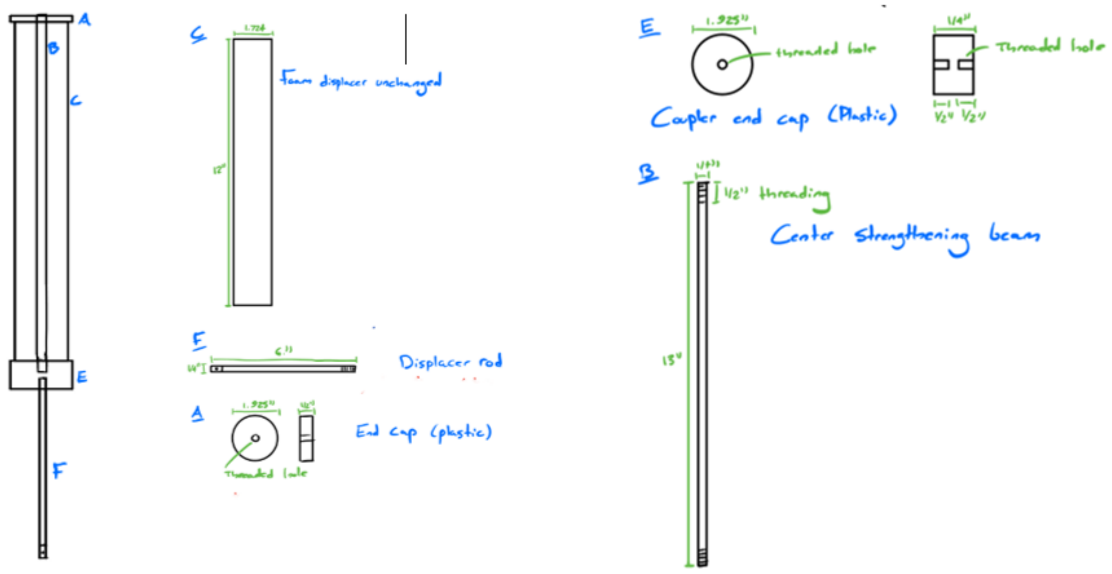

Figure 12: Displacer design with extruded components.

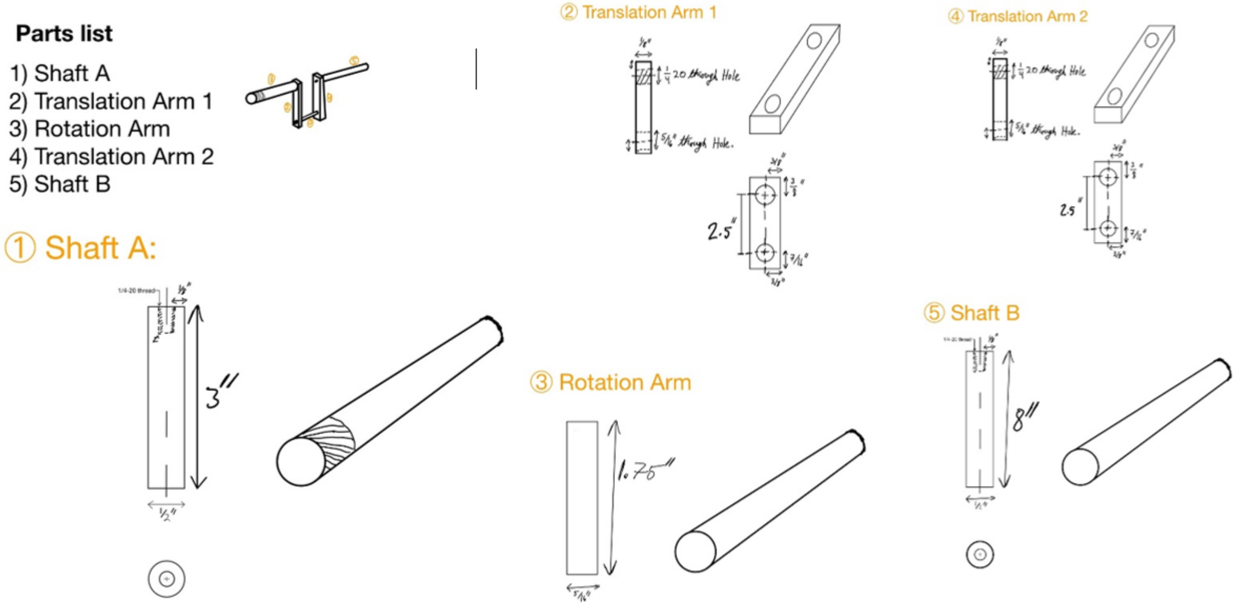

Figure 13: Drive shaft system with extruded parts

Appendix B – Bill of Materials

The total cost of all materials used to create the 1/50th scale prototype project are outlined in Table 1.

Table 1: Bill of materials for the design of a Stirling engine including all materials ordered and for materials available without purchase an equivalent part is provided and cost.

Material	Volume	cost (CAD)	Purchase location
Heating System			
Fresnel Lens	1	$46.49	Grandado
Wood for stand (2x4x96 inch wood)	3	$3.90	Home Depot
Wood Screws (12 2inch screws)	1	$13.00	Home Depot
System Total Cost		$71.19	
Pumping System			
Drill Pump	1	$14.99	Amazon
1/2-inch plastic Tubing (1m)	1	$12.99	Amazon
Clamps	3	$10.99	Amazon
Plywood 2x4	2	$3.98	Home Depot
System Total Cost		$68.91	
Stirling Engine			
Insulating Foam	1	$24.97	Home Depot
3" Abs Pipe	1	$12.96	Home Depot
3.5" Aluminum Cylinder	1	$57.31	McMaster-Carr
3" abs coupler	1	$1.00	Home Depot
Fly wheel	1	$89.58	McMaster-Carr
3/4-inch aluminum sheet	1	$59.39	McMaster-Carr
Barings	2	$6.57	McMaster-Carr
1/2-inch shafting	1	$9.27	McMaster-Carr
Vacuum shaft seals	1	$4.95	McMaster-Carr
vacuum grease	1	$29.82	McMaster-Carr
Air Piston	1	$28.68	McMaster-Carr
1/8 " Shafting	1	$10.56	McMaster-Carr
Shaft connectors	3	$14.95	McMaster-Carr
System Total Cost		$341.63	
Total Cost		$481.73	

The costs associated with making the full-scale Stirling water pump are outlined in Table 2.

Table 2: Bill of materials for the design of full-scale Stirling engine including all materials ordered and for materials available without purchase an equivalent part is provided and costed.

Material	Volume	cost (CAD)	Purchase location
Heating System			
Fresnel Lens	0.86	$234.24	Grandado
System Total Cost		$201.45	
Pumping System	-	-	-
Commercial pump	1	$720.00	Grainger Canada
System Total Cost		$720.00	
1/50th Scale Stirling Engine			
Insulating Foam	1	$24.97	Home Depot
3" Abs Pipe	1	$12.96	Home Depot
3.5" Aluminum Cylinder	1	$57.31	McMaster-Carr
3" abs coupler	1	$1.00	Home Depot
Fly wheel	1	$89.58	McMaster-Carr
3/4-inch aluminum sheet	1	$59.39	McMaster-Carr
Barings	2	$6.57	McMaster-Carr
1/2-inch shafting	1	$9.27	McMaster-Carr
Vacuum shaft seals	1	$4.95	McMaster-Carr
vacuum grease	1	$29.82	McMaster-Carr
Air Piston	1	$28.68	McMaster-Carr
1/8 " Shafting	1	$10.56	McMaster-Carr
Shaft connectors	3	$14.95	McMaster-Carr
System Total Cost x 50 scale		$17,081.50	
Total Cost		$18,002.95	

Appendix C – Optical Testing results

Results found from optical testing are presented in Table 3 and Table 4.

Table 3: Results from measuring optical power at focal point with and without the lens.

Trial	With the lens (Watts)	Without the lens (milliwatts)
1	2.07	2.8
2	2.01	3.2
3	2.01	3.3
Avg	**2.03**	**3.1**

Table 4: Power output at various positions beneath the lens

	Power (milliwatts)			
Position	Trial 1	Trial 2	Trial 3	**Average**
1	0.051	0.056	0.058	**0.055**
2	1.11	1.1	1.222	**1.144**
3	0.49	0.435	0.391	**0.438667**
4	0.054	0.054	0.053	**0.053667**
5	0.055	0.055	0.054	**0.054667**
6	0.044	0.044	0.044	**0.044**