SOLAR POWERED RESONANCE PUMP

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Abstract

This study investigates the suitability of a solar powered pump for irrigation purposes in Sub-Saharan Africa, where solar power is used to pump water from wells and help farmers improve their living conditions. This system uses solar power due to a lack of electricity in rural areas of the region and therefore, several solar powered projects have been undertaken which have attempted to make use of the region's constant sunlight and hot weather conditions. For this particular reason, this report focuses on analysing a Solar Powered Irrigation Resonance Pump (SPIRP), which is a solar thermal powered pump with no moving parts that can address the energy trilemma as being clean, affordable and provide a reliable supply with little maintenance or supervision. Qualitative data were used to analyse the principles of the pump system and quantitative research was used to confirm the understanding of the system's operation. The analysis shows different principles, and a steam model is used as a proposal for the system working principles. It is concluded that the system might operate in this condition and further analysis may be required.

Acknowledgement

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Lilia Luis

Table of Contents

List of Figures

List of tables

List of Abbreviations

PV	Photo-voltaic
DC	Direct current
AC	Alternative current
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
GTI	Global Tilted Irradiance
GDP	Gross Domestic Product
LPSE	Liquid piston Stirling engine
SPIRP	Solar powered irrigation resonance pump

List of Symbols

f	frequency
ω	Angular frequency
At	Output cross section area
Lt	Output length
m	Mass
g	gravity
Pm	Mean pressure, Pa
Vm	Gas volume, cm^3
ρ	density, kg/m^3
Ld	Total length
Ad	Engine columns cross section area
P_o	Pressure, kPa
k	Spring constant

Chapter 1: Introduction

1.1. General background

Electricity is a form of energy that has played a significant role to humanity since its connection with lightning was established by Benjamin Franklin in the 1750s. In this time period, electricity was expected to be distributed worldwide, however, 840 million people live without electricity (International Renewable Energy Agency [IRENA], 2019).

In areas where limitations are significantly high due to a lack of electricity and water, people conduct regular activities during daylight but after sunset they are limited to certain activities as energy is not available to fulfil basic needs, including providing an available source of water to drink, to use on subsistence agriculture and other applications (Riva et al., n.d.). For example, some people rely on generators which gives them enough energy security to continue their activities, however, other citizens may not be able to afford the electricity costs to guarantee energy security. Furthermore, access to electricity has been a significant concern in rural Sub-Saharan African communities, as grid electricity is not often widely distributed. For instance, the International Energy Agency (2019) estimates that 600 million people do not currently have access to electricity. Additionally, in 2008 the Food and Agriculture Organization concluded that almost 40 percent of people do not have access to clean drinking water and 70 percent lacked appropriate sanitation. This therefore increased the vulnerability to being at high risk of malnutrition, poverty, decreased school attendance and missed workdays (FAO,2008).

For farmers, not having the right resources to be productive in their daily activities makes it harder for production and consumption, affecting everyone. Several farmers for irrigation systems still use treadle pumps or canals to collect water, which is the best that they have so far, but not ideal when they can also benefit from new technology and perhaps in a more sustainable and ecological way (National Institute of Food and Agriculture [NIFA], n.d.). There are good attempts of such good projects using solar energy, from solar pumps and windmills to power electric water pumps that will be addressed in this project. For instance, in 2014, Harishankar et. al have proposed a solar pump design requiring minimal maintenance. Some of these projects have been tested in some villages, although some of them never passed to the industrial stage it is always good to find a way of starting somewhere.

Solar thermal powered pumps, if well implemented, can possibly change the future of rural areas, and it is therefore important to obtain an in-depth understanding of how this system works. While there have been several studies on a proposed solar powered resonance pump design by Dennis Carey, none has focused specifically on the system fundamentals. Moreover, as the system has been related to a Stirling piston engine in previous research, it is crucial to expand the knowledge from there and start to understand its operation.

1.2. Aims

The aim of this research is to investigate the suitability of a solar thermal powered pump for irrigation in Sub-Saharan Africa, in particular a pump with no moving parts proposed by Dennis Carey which will be introduced in the thesis.

1.3. Project Objectives

- Analyse qualitative research to understand the background of irrigation systems to identify what type is needed.
- Gather information to gain an overview of opportunities for solar powered pumps in Zambia.
- Investigate the specific solar pump and determine a valuable solution that is suitable for rural areas.
- Research different principles that can possibly give a full comprehension of the system operation.
- Test the prototype to confirm the understanding of the system operation.

1.4. Structure of the project

Chapter 1 gives a generic introduction about the area of research, where the reader will understand details about the topic and comprehend the reason why this subject was chosen with the aim and objectives. This chapter also outlines the different types of research methods considered and clearly defines the approach used for this project.

Chapter 2 explores different journals, conferences which are relevant to the topic area, summarising previous results to help the development of the system. In this chapter a clearer understanding of why this report is chosen is also discussed. This chapter also looks at different principles that are connected to the basic principle of operation of the solar thermal powered pump.

Chapter 3 examines the solar resource and pumping availability in Zambia, showing the agriculture scenario of the area.

In **Chapter 4** a characterisation of the system is made where it considers the solar energy information to drive the concept of the source of heat used in this project. Notably, a description of the solar collector is given with recent innovations of materials available in the market. With this being given it leads to a final proposal for improvements of a flat plate collector for the current system.

Chapter 5 attempts to explain the operation of the solar thermal powered pump, it briefly describes the concepts linked to its functionality allowing an improved conceptualization of the system.

Chapter 6 is where the results obtained from the experiments are illustrated. Also, the findings from the previous chapters are discussed and critically analysed.

Chapter 7 draws conclusions from the research project. It states the advantages of this type of pump rather than other types available in the market. It further outlines the implications of the research done by people already working in this field. Chapter 7 also gives a direction of where further research should go.

1.5. Research Method

The strategies used in the collection of data to produce this research integrate qualitative and quantitative research. There are a variety of tools that researchers can take to conduct their studies, ranging from interviews to surveys, from document analysis to experiments and oral stories dividing them into qualitative and quantitative techniques. For this research project, a variety of techniques is used for the success of the project.

Table 1- Research Method.

Qualitative tools	Quantitative tools
Document analysis: journal articles, reports, conference papers.	**Observation**: counting the number of times a specific phenomenon occurs.
Oral history or life stories: personal communication with Local farmers in Zambia.	**Experiments**: testing in laboratory.

1.5.1. Qualitative tools

Using the qualitative tools described above such as document analysis, has led to researching data from previous reports and papers to develop a better understanding of the solar powered resonance pump. From this, most of the theory was comprehended. From an oral history tool, certain perspectives of the area where the project is intended for implementation was given, giving an attribution to the report. This was possible due to a virtual discussion with local farmers in Zambia.

1.5.2. Quantitative tools

On the other hand, using quantitative tools such as experiments was crucial as the project is mainly based upon practical work. To complete this project, different types of experiments were performed, ranging from initial set-up to observing the movement of the water, to measuring pressure fluctuations. Following this experimental approach, a new pump was made incorporating clear pipe sections to observe water oscillation inside the pump and measure pressure fluctuations with manometers being attached to the system. Additionally, a third pump was then built with new adaptations to incorporate sensors and thermocouples so that pressure fluctuations could be measured with accuracy.

Chapter 2: Literature Review

2.1. **Traditional methods ever used in irrigation systems**

It is surprising how the world has seen different techniques for irrigation systems applications. From human power to technology, such as waterwheels and solar powered pumps (Yannopoulos et al., 2015). Different approaches have been utilised and are still in development in a search for the most effective and appropriate one. For developed countries, technology has taken the place of human labour, while in less developing countries people still have to do relatively simple jobs to acquire their daily basic needs. In farming, children and women are still required to undertake this particular activity as mentioned before (Food and Agriculture Organization,2011).

Research undertaken by Yannopoulos et al. (2015) seems to indicate that since the ancient times manners of extracting water for irrigation have been used, an example is a device known as a shaduf. This device is still being used in Egypt and in India as it helps people raise water from the well (Mirti, 2001). It works as wooden hand operated device, mounted with a long wooden pole and it has a rope attached to one end of the pole and a counterbalance to the other end as shown in fig 1. This pole is pulled down by the operator, a container is filled with water, allowing the counterweight to raise up the container (Yannopoulos et al., 2015). A limitation to this is that it requires human labour to operate, and in most areas children and women have to operate it, which restricts them from undertaking other activities such as attending school. Another limitation is that this technique is not quite applicable to deeper levels of underground water.

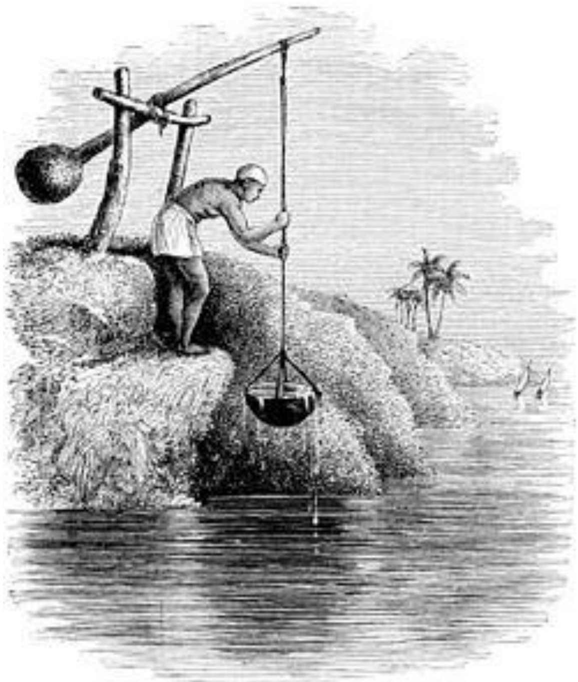

Figure 1- A shaduf device (Mirti, 2001)

A further method that has been commonly observed in irrigation is the ‘Waterwheels’ system. Yannopoulos et al. (2015) stated that this device, also known as Noria, was the first vertical axis waterwheel to be implemented by the Romans. The system consists of buckets being attached to wooden wheels in series that are powered by water flow for irrigation purposes as shown in fig 2. This method was then introduced in different areas and in different forms. In Asian countries for example, the technique was driven by camels to lift water (Yannopoulos et.al,2015). The limitation of this technique is the required use of animal labour. These types of devices are no longer attractive to irrigation systems scenarios because of the muscle energy required.

Figure 2- Noria irrigation system (Trevor,2013)

Another common system in the irrigation sector is the treadle pump which is known for being relatively less expensive than conventional pumps. Nevertheless, its operation requires human labour. Treadle pumps were analysed, and Polak (n.d) investigated a human powered water lifting device that could lift seven cubic meters of water from wells and bore holes from 7 meters' depth. It consists of twin cylinders attached with pistons that rise and fall with the pressure of an operator standing on the treadles in a walking motion. Inside the cylinders a pressure is created, and water enters the pump cylinders through an inlet pipe. At the end of this pipe a non-return valve is attached so that water enters in the pipe, and it prevents to not flow back to the water (Yannopoulos et al., 2015). This device led to an increase in both farming output and incomes. The main concept of the system is to pump water by using pistons which can be operated by a stepping motion (Polak, n.d.). This method was successful because it was less expensive than conventional pumps, it had no fuel requirements and demanded limited maintenance costs are required.


Figure 3- Treadle pump (Engineering for change, n.d.)

Most of the traditional methods discussed were operated by human labour, which is what new technology in this sector is attempting to minimise. With the use of systems that can self-operate these people can possibly attend to other functionalities. For instance, not having to actively operate the device may allow more children to go to school.

2.2. Development of Solar Powered Stirling Engines

Stirling engines have been studied since the 19th Century. It was invented by Robert Stirling in 1816 (Reid, 2016) shown in fig4. Further on, in 1870 Ericsson adapted the principles to operate with solar energy. From the adaptations made by Ericcson, Meinel and Meinel (1976) reported that those results would be economical for remote areas. Reader and Hooper (1908) proposed for the first time a solar Stirling engine for water pumping systems. After years of researching in the area, further studies were conducted, and new ideas generated. West in 1976, outlined the performance that could be achievable for Stirling engine irrigation pumps using a single liquid piston engine suitable for manufacture in less developed countries. Similarly, Dennis Carey worked with West in developing the Fluidyne in the 1970s, which resulted in a solar powered pump with no moving parts, and no need for grid electricity. The system patented by Carey in 2000 was adapted from a Fluidyne engine.

Based on studies mentioned above, the objective of the project is to study how the Carey pump could potentially be applied in Sub-Saharan Africa analysing each parameter to understand the principles and then scale it to the field. Starting from knowing that Carey's solar heat powered pump worked effectively from June 1999 to August 2002 with evidence from his field trials, however, the physics behind it were never revealed, leading this project to a challenging research. For several years this project was kept in the silence, until Carey's daughter decided to carry on developing this technology. The project was brought to the University of Huddersfield a few years ago and since then, research has been actively on to understand exactly what principle of operation drives the system by reverse engineering it. The challenge is now to replicate it to understand how it functions to be able to model and scale it to a larger size. One of the Careys prototype pumps is the basis of the work that is being carried out in the university, and therefore looking at Stirling engines is important, as Carey believed that Fluidyne engines are the key feature to the principle of operation. The solar heat powered pump was identified as a potential suitable method for rural areas, because it has no moving parts, uses solar energy, it does not wear out, it is a good idea, but it needs to be understanded properly and scaled to the right size. This pump is further described in the system background in the next chapter.

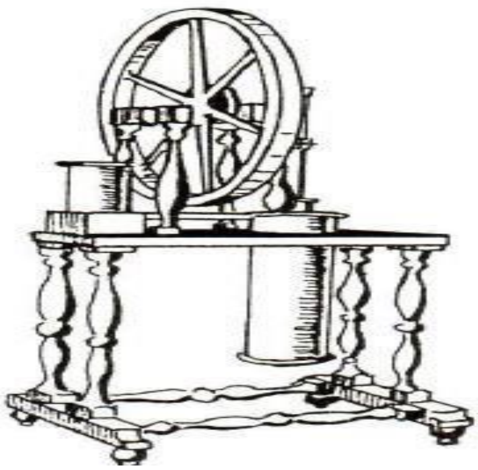

Figure 4- - First version of a Stirling Engine by Robert Stirling (Wikipedia, n.d.)

Consequently, researchers came to an agreement that Stirling engines can use solar energy, able to be built as a more economical power source for developing countries (Kongtragool and Wongwises, 2003).

2.3. **Liquid Piston Stirling Engines**

The Stirling cycle is known to be one of the most efficient thermodynamic cycles (Thombare & Verma, 2008). Notably, a cycle capable of equalling the theoretical efficiency of Carnot implies the potential of manufacturing high-efficiency engines (Motamedi,2018). In general liquid piston Stirling engines have been found to be inexpensive, reliable, and environmentally friendly (Langdon-Arms et al., 2017).

A Liquid piston Stirling engine (LPSE), also known as Fluidyne, uses liquid columns of water in the place of solid pistons (Langdon-Arms et al., 2017). This system has led to water pumping systems based on the engines being developed. The basic functionality and design of a Fluidyne is firstly shown by West (Elrod,1974) in fig 5. The researchers also explored the dynamic complexity of LPSE by investigating and formulating formulas on thermodynamics equations to solve them numerically proving that LPSEs are far more economical than the conventional engines (Motamedi, 2018).

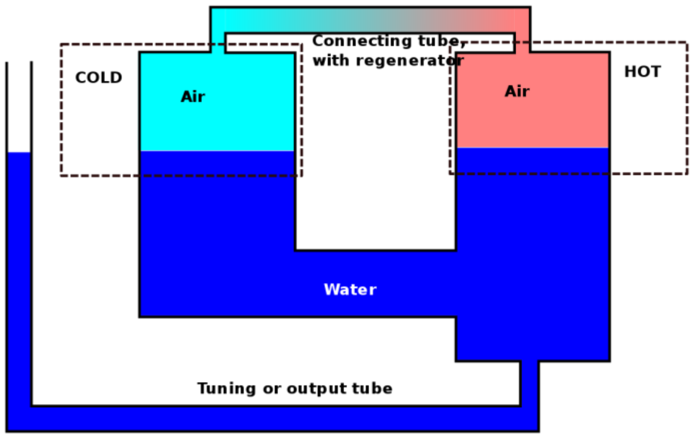

Figure 5- Diagram of a U-tube Fluidyne engine proposed by West (Wikipedia, n.d.)

Furthermore, West (1987) has highlighted that simple engines can be suitable for manufacture in less developed countries. From what he has presented, an engine used to drive a pump, formerly the power can be used to raise liquid that in that case could be the water.

In addition, Elrod (1974), stated in his report how the construction and performance of a Fluidyne, analysing from a thermodynamic perspective. He also showed that once the temperature difference from the hot side and the cold side achieves a critical value, oscillations will automatically commence. This phenomenon calls attention to this research project because the temperature difference is one of the parameters that will be examined throughout the research. Additionally, West presented a definitive explanation of his Fluidyne piston Stirling engine, by using theory to prove how the engines work, as well as explaining how to design and build one. This implies that the concept design leads to an easy-to-build device with a variety of simple tools and materials and, more importantly, West investigated how to increase the power output. This particular study looked at initial work being presented at Harwell in terms of two reports. The reports describe the principles of the engine and experimental confirmation of liquid feedback. Nevertheless, it did not show evaporation being suppressed from the machine and particularly its efficiency was relatively low. The weakness there was the wrong implementation of the theory. This calls attention to effects of oscillating flow on viscous losses and heat conduction not being known to the writer at that time. The findings may have been more applicable if the principles in the transient heat-transfer loss had been applied to the study.

Research made by Langdon-Arms et. Al (2017) shows that thermo-mechanical cooling systems use the heat that is generated by the solar collector to drive the heat engine which is similar to the solar powered pump in use. Stirling-based cooling systems require work input to be operated.

2.4. **Solar pressurized liquid piston Stirling engine**

Further research undertaken by Motamedi (2018) proposes a solar pressurizable liquid piston Stirling engine that contains a working gas, hot and cold column, tuning column, regenerator, power piston, check valves and output water tube. From this, the heat source is a solar collector that absorbs the heat from a Fresnel lens and transfers to working gas. On the other side it has a cold heat exchanger.

This research was relevant because the system works according to a gas pressure variation, when the pressure is relatively high, the pressure applied on the liquid piston will overcome the static pressure allowing the water to be pumped at the output column. This finding is significant because it gives an overview of the pressure working on the system that will allow this project when looking at cyclical pressure variation to better understand the system. One of the limitations towards the solar powered pump when compared to this system is that no regenerator and check valves are used, making the solar powered irrigation resonance pump (SPIRP) a simpler system.

Final remarks

As far back as 1985, West highlighted that simple engines were suitable for manufacture in less developed countries. Understanding the Liquid piston Stirling engine or Fluidyne engine is fundamental to this project as their principles underlie the operation of the system designed by Carey, the SPIRP. Therefore, it was important to undertake a review of what has been said and it is currently being studied, where the connection of features including simplicity, durability, and no solid moving parts, were taken into consideration and it plays a significant part in the SPIRP.

2.5. **Solar Powered Pumps**

Since ancient times, pumps have been widely used for irrigation purposes (Yannopoulos et.al,2015). They have been used in a variety of forms such as Persian wheels, and all of them with their complexity. With the historic development of Stirling engines mentioned above, it led to today's implementation of solar irrigation pumps. With great technology is possible to optimise systems with higher performance. For instance, Golben (1989) patented a design where a heat exchange circuit combined a solar collector and a compressed gas engine, but the circulating pump requires a direct current (DC) electricity for its operation. In this same order, Braunstein and Kornfeld (1981) have analysed solar powered pumps using an electric motor, and their studies led to great contributions to enhance the design of solar powered pumps.

Further, Harishankar et. al (2014) proposed a design solution that optimizes the usage of water and reduces human intervention for farmers. Despite being self-starting and requiring minimal maintenance, it has been found to require high capital investment to be implemented. Their model has an intelligent algorithm that regulates water flow into the field.

Considerations are made when using solar collectors as heat input for power generation (Kongtragool et. al, 2003). From their theoretical work, it was concluded that in order to improve the performance, a good heat transfer to the working fluid is required. This means that high values of mass flow are needed and reduce pumping losses with lower viscosity in working fluid.

In addition, in 2009 Ramos and Ramos studied a solar powered water pump that could include a battery bank or a storage tank. Their findings indicate that using a water tank is preferable as batteries turn the project relatively expensive and require specialised works.

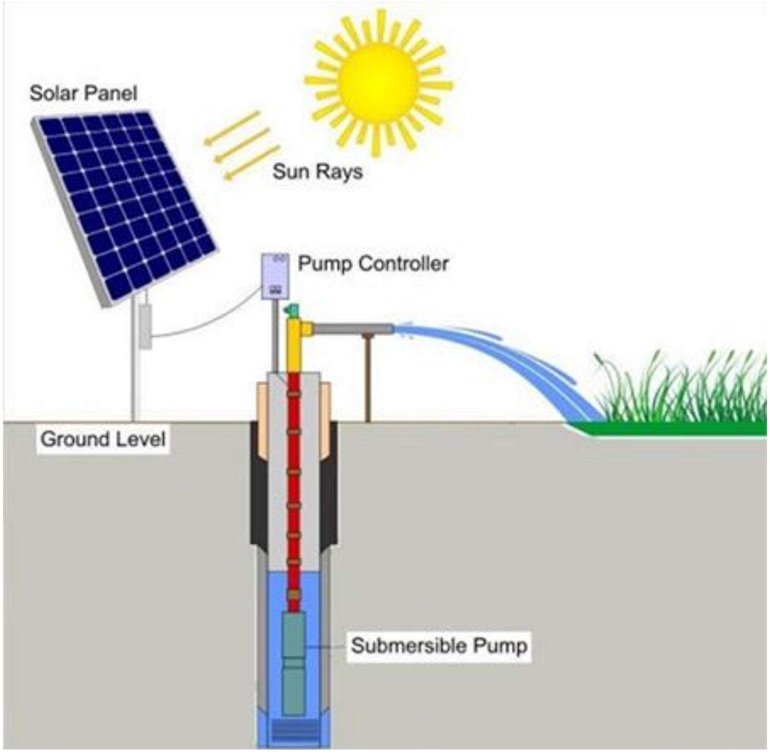

Figure 6- Submersible solar powered pump (Indiamart, n.d.)

Different types of photovoltaic (PV) powered pumps are available in the market such as submerged solar pumps as shown in fig.6, electric pumps, and diesel pumps. These technologies tend to be an attraction to the agricultural sector due to the large power range of the pumps, but the intense and skilled maintenance requirements make these systems a costly solution in the long run (Emde, 2004).

One common type of solar pump is the PV pump. These pumps use photo-voltaic panels to generate electricity in places which lack electricity. A major issue with these systems is that components and materials are at extreme risk, as they might get stolen to fulfil other people's needs at home. However, these systems are good as their application significantly helps the agricultural sector (Shinde & Wandre, 2015). Additionally, these systems operate on Direct Current (DC), and the produced DC from the panel is sent to the controller and then directly to the pump (Shinde & Wandre, 2015). The pump works at high speed, a greater speed pumping a greater volume of liquid, when the sun's irradiation is high, thus, more current is being transferred to the pump and more water is pumped.

Alternatively, **solar thermal** technologies have the possibility of local production, with easy maintenance highlighting a much more attractive solution for irrigation systems in meeting the needs of remote communities.

Conclusion

This chapter has underlined the history of devices used for irrigation systems. From the ancient times until today. The use of modern technology may positively impact rural communities. It is observed that conventional water pumping is expensive for people living in rural areas making solar thermal technologies a viable solution and adding an advantage to this report that relies on a flat plate collector powered pump.

2.6. **Solar Powered Resonance Pump**

The system proposed is intended to provide access to affordable, clean, and sustainable energy sources to support the provision of water for communal household water supply use and for field and market garden irrigation in rural and semi-rural areas in Sub-Saharan Africa. This is currently restricted, as these areas experience an irregular (non-renewable) electric supply. They rely instead on manually operated labour-intensive treadle pumps or motorised centrifugal pumps, which are expensive to purchase and to run. This places a heavy burden on women and children who are often responsible for water collection and undertake a lot of the farm work related to subsistence food production. Research shows that the primary responsibility for water collection in over three quarters of households is held by women and children (UNICEF, 2016), taking those children away from schools. This has a great impact on gender equality and social inclusion as much of their time is spent manually transporting water from wells or operating treadle pumps for domestic and agricultural use.

To support such rural populations, it is imperative to have affordable, simple, and efficient solutions to supply water and mitigate, or solve, the issues related to hunger and drought. The proposed solution is a SPIRP, a solar thermal powered pump with no moving parts. It will address the energy trilemma as being clean, affordable, and providing security of supply.

- It uses heat energy from a solar collector to generate oscillations in a column of water which is targeted to lift water up to a height of 3 meters from wells or boreholes and delivers a steady flow of water at a rate of 17 litres per minute.

- It is low cost with a simple design with no moving parts and the potential to be manufactured locally using easily available or recycled materials. No maintenance is required, which lowers fixed costs.
- Being powered by renewable solar energy and based on temperature fluctuations, it has the potential to consistently provide a steady flow of water during daylight. No specialist skills are needed, and minimal pump maintenance downtime is envisaged, adding to the security of the supply.

The pump has three major elements: a solar thermal collector, a solar engine (based on the Stirling engine principle) and a resonance lift pump. The solar collector heats a volume of air in the heat engine which drives an oscillating loop of water acting as a liquid piston. The resultant pressure pulses from the solar engine drives the resonance lift pump. The design is unlike most documented Stirling type engines in several aspects. First of all, it is a liquid piston device, using an oscillating loop of fluid to generate output power. Secondly, it uses the liquid being pumped as a heat sink to maximise the temperature difference between the hot and cold sides of the engine. Thirdly, it is a double-acting system, essentially two Stirling engines back-to-back, so theoretically has a much greater efficiency than a standard Stirling engine.

2.6.1. System Background

The SPIRP pump concept was designed in the 1980s by Dennis Carey for potential application in the farming industry in Sub-Saharan Africa (Vinter,2017). This application was never realised, and the design lay dormant until after Mr Carey's death in 2012. His daughter is now working with engineers at Huddersfield University using modern technology to refine the pump's design for farming in rural areas. It does not necessarily require special skill to use it nor any servicing. Another key feature of the pump is that it can cope with dirty water. It looks simple, however, it requires a complex design (Vinter, 2017).

It is thought that the invention is based on a Fluidyne Stirling engine, which is a no-mechanical-moving-parts Stirling engine that works by alternately heating and cooling a gas in a confined space, causing pressure oscillations and movement of liquid in the system (West, 1977).
From this concept, an adaptation is made for the solar powered pump where Carey (1998) used a single closed loop 'U-tube', having a single one-way valve only.

Therefore, as shown in fig 9, two legs containing water (14A and 14B), the ducting loop connected to inlet ducting (16) and the outlet to be pumped (18). The inlet should have higher hydraulic resistance than the outlet ducting. A solar collector (12) is used to maximise the heat input (Carey, 1998). The solar heat causes air in the ducting loop to expand pushing the water in the legs (14A and 14B). Temperature will start to oscillate at a certain temperature at its natural frequency, allowing an intermittent outflow of water from outlet ducting (18).

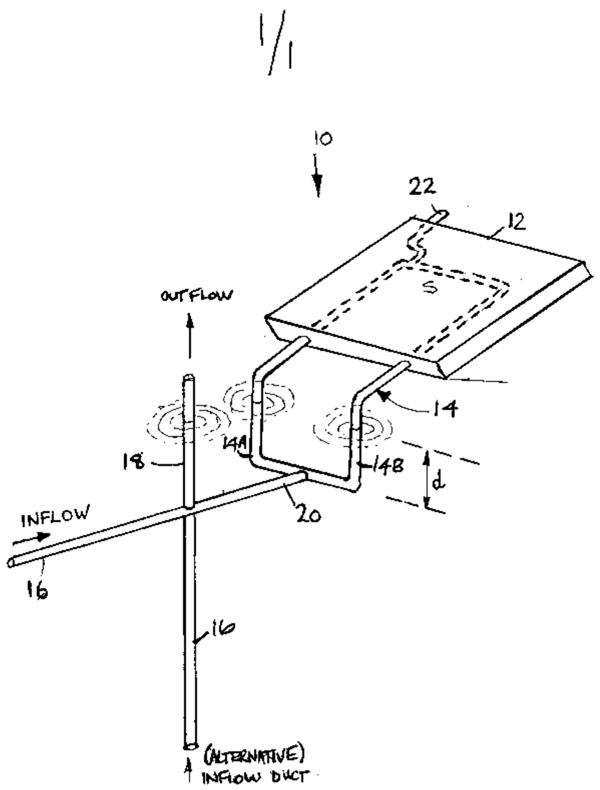

Figure 7- Diagram proposed by Dennis Carey (Carey, 2000)

2.6.2. Operational principles

Standing and Travelling wave engines

The standing wave engine usually refers to the self-sustained oscillator that contains a gas column confined in a resonance tube with open-closed ends. In addition, the thermal efficiency of generating the acoustic power from heat never reaches the 'Carnot efficiency' because of the irreversible heat exchange of the gas with the stack walls.

The traveling wave engine is made of a looped tube filled with the working gas. It has a differentially heated regenerator. In the regenerator region, the working gas maintains a good thermal contact with the solids. The thermal efficiency of generating acoustic power from heat can reach the 'Carnot efficiency' (if taking aside the viscous damping) because of the isothermal thermo- dynamic processes in the regenerator.

Huelsz's engine is categorized into the standing-wave engine since the phasing between pressure and velocity must be close to $\pi/2$. If the liquid column goes up in the horizontal tube towards the bulb, the gas in the neck also goes up, resulting in the increase of pressure. The gas displacement and pressure are therefore in-phase, and because the velocity oscillation leads the displacement oscillation by $\pi/2$, the standing-wave phasing is achieved.

Whereas the Fluidyne engine is a traveling-wave engine, the traveling wave phasing is achieved in the regenerator, when the oscillation frequency is equal to f_0. It should also be noted that the tuning column must be connected to the 'U-tube' asymmetrically.

Steam Model

Crane (1997) describes the principle by heating a small candle inside the boat that will make it eject pulses of water from tubes at the rear just under the water level, at five or more per second. That propels the boat at 10 cm/s or more, and it will go for as long as the candle burns. This steam model can potentially be the solution for what is expected on a full understanding of this solar thermal powered pump.

This model might indicate a proposal of a different way that the system may be working. Taha (2016) studies a toy known as putt-putt boat which physicists have long been investigating. It is known as a simple steam engine with no moving parts that requires heat as a source of energy. It works using a thermodynamic principle.

Description:

- No moving parts
- Steam engine
- Powered by a candle (heat)

The system contains a boiler connected to an exhaust tube. When the boiler is heated, the water evaporates producing steam, allowing this steam to be pushed out of the boiler, pushing some water out of the exhaust tube. When the boiler is dry, meaning that, steam is being generated. The steam in the engine condenses, which creates a vacuum which sucks fresh cold water back into the engine and allows the cycle to restart (see fig.8).

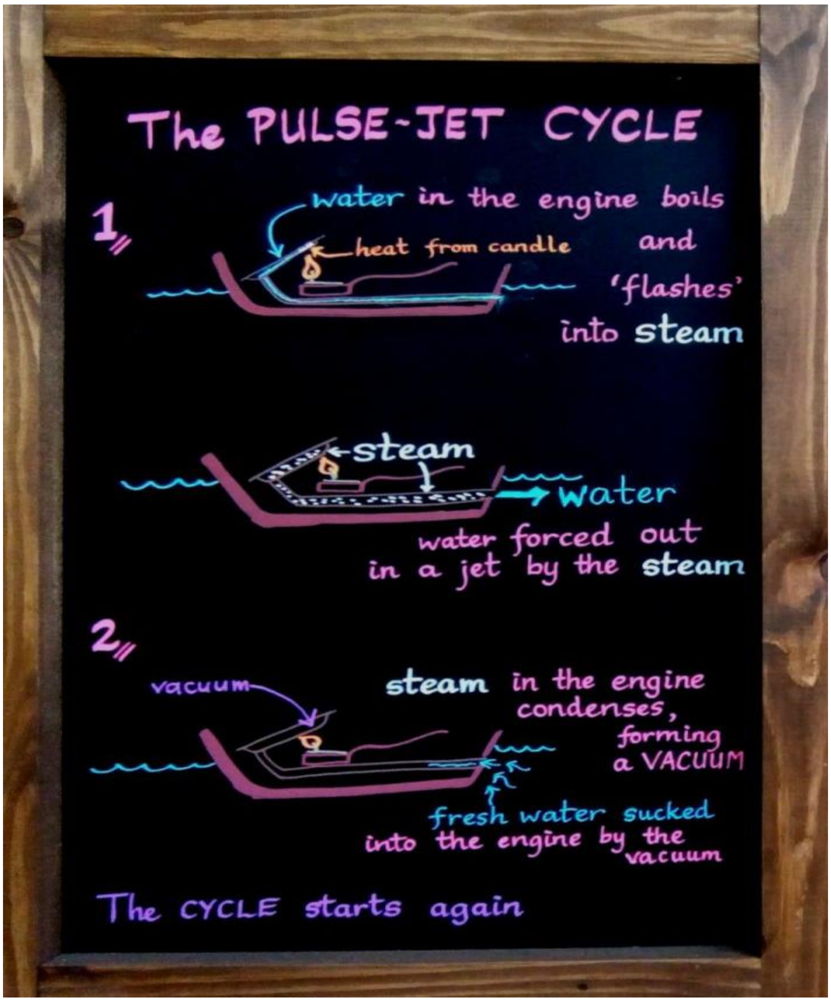

Figure 8- Putt-putt boat cycle (Poppopboats, n.d.)

This way of visualising the model from its descriptions makes it clear, assuming a simple working principle.

If the solar thermal pump is tested with water filled in the collector, different results such as the system operating with higher amplitude might occur, and a solution for where the system belongs to which operating cycle may appear.

Chapter 3: Solar Resource in Zambia

This section gives an overview of solar energy availability in Zambia, starting with the actual scenarios of their available irrigation systems. From the figures that follow, some information is reported in terms of irradiation around that area to give a general overview from where the project is set for implementation.

Firstly, Zambia is located in Central Southern Africa. Research shows that Zambia gets an average of 2000 to 3000 hours of sunshine every year (Silimina,2020). The country has great potential for solar energy applications in general, despite solar panels not requiring substantial sunlight to work with. Furthermore, the country has a high level of solar irradiation as a high amount of power can usually be collected from the sun (Silimina,2020).

Considering the use of flat plate solar systems is important to observe GHI values. From looking at Global Horizontal Irradiance (GHI) values you can estimate the amount of radiation received by a surface horizontal to the ground and calculate the performance of a collector. The figure below shows where the highest GHI is identified in the country. With average daily sums reaching 6.3 kWh/km2 (yearly sum about 2300 kWh/km2) (Solargis,2019).

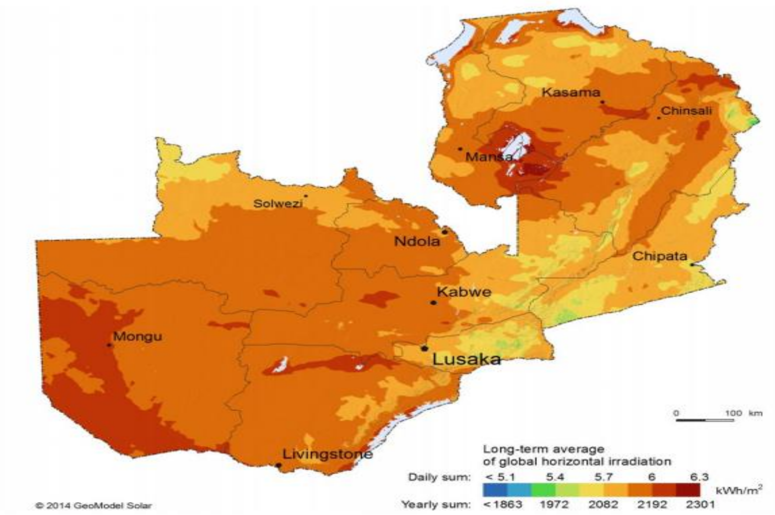

Figure 9- Daily and average sun reach points in Zambia (Solargis, 2019.)

3.1. Agriculture Scenario in Zambia

The agricultural sector in Zambia contributes to approximately 20 percent of Zambia's gross domestic product (GDP) (World Bank, 2012). According to the Food and Agriculture Organisation (2014), this sector provides 60 percent of the country's labour force where 80 percent of employed people living in rural areas work in agriculture. Furthermore, although the country has abundant arable land, only 14 percent of it is suitable for production and less than 30 percent is suitable for irrigation has been explored. In addition, there are 600 000 smallholder farmers. However, modern technology for irrigation systems is still not very popular in Zambia, as production is making crops highly vulnerable to fluctuations (FAO,2014).

According to Muchimba (2020), developments in the Zambian irrigation industry are divided in two-fold, from the commercial side and small-scale side. The commercial side has seen rapid growth due to the crisis in Zimbabwe and South Africa (Hammar,2010). There has been a significant migration of commercial farmers into the country (Muchimba,2020). In recent years, the country has seen thousands of hectares come centre pivot irrigation, there has been a shift to low flow irrigation systems like drip for new crops (FAO,2014). This is due to low commodity prices for traditional crops. In fact, most commercial cropping is done by using Hydroelectric driven motors. Furthermore, commercial farmers growth is driven by access to funds from banks and foreign investment funds (Muchimba,2020).

On the other hand, Muchimba states that small-scale farming has not seen rapid growth compared to commercial. There is a lack of access to loan facilities, as well as climate change effects which in some cases has brought up low rainfall patterns and floods (FAO,2019). Farmers along hydrological systems like rivers and streams have been able to grow vegetables throughout the year using treadle pumps and fuel motors pumps (Muchimba,2020). Also, shallow wells for water sources and then use solar pumps for abstraction are used by some farmers (Muchimba,2020).

3.2. Irrigation Systems in Zambia

Irrigation not being powered by human labour has significantly changed the agriculture sector (FAO,2014). Unreliable irrigation systems seem to be a very common issue for Zambian

agriculture but implementing the solar powered pump will suppress this pertinent issue. Farming helps small communities sustain themselves, making a significant contribution to people who live in those areas as it may provide food for the entire community.
One of the problems related to irrigation systems in this country, is the lack of access to electricity. For example, the Food and Agriculture Organisation (2014) found that access to the power grid is one of the main barriers to expanding irrigated agriculture in Zambia. Pump-based irrigation systems generally require electricity apart from other emerging solar options.

A range of renewable energy equipment for use in irrigation is often offered by irrigation suppliers, such as AC and DC pumps, photovoltaic solar panels, controllers, and inverters. These options have arguably helped farmers attempt to pump systems. In addition, submersible pumps are available on the Zambian market, although the cost of it makes it not accessible to everyone.

Figure 10- Scenario of a small-scale farmer using canals and treadle pumps in Zambia (P. Muchimba, personal interview, September 18,2020)

There is a high competition for supplying irrigation equipment, however, in the country there is no local manufacturing. Thereby, farmers depend on certain suppliers for irrigation equipment. There is also a lack of information in prices for equipment, so some farmers usually buy pumps from expensive retail.

Being able to understand Zambia's scenario in farming and agriculture gives a significant clarification on where the system is projected for installation. Adding knowledge for what is currently happening there so that actions could be taken. From that understanding more effort should take place to help farmers suppress their needs, as their facilities still rely on treadle pumps or fuel motors pumps. From what has been tested in the solar collectors at the university and comparing their radiance values throughout the year will not be a problem installing the system and having it on during the year.

Chapter 4: Characterisation of the System

In this chapter, the system is characterised considering the source of heat used in the project. A description of the solar collector is given with recent innovations of materials available in the market. The idea is to analyse different materials that have an impact in the performance of the flat plate collector and possibly design one to compare the performance with the one used in this project.

4.1. **Solar Energy**

Solar irradiation is defined as the amount of solar energy that falls on a unit area on a stated time interval, usually measured in Wh/m^2 or kWh/m^2 (Solargis, n.d.). The sun's output energy is not constant.

Radiation to reach Earth's surface takes a long process, thus, various interactions between solar radiation and objects need to be considered (Solargis, n.d). There are some parameters that are used in practice:

- Direct Normal Irradiance (DNI)
- Global Horizontal Irradiance (GHI)
- Global Tilted Irradiance (GTI)

When looking at concentration, researchers will refer to DNI. When referring to the sum of direct and diffuse radiation on a horizontal plane the option will be GHI, more specific to comparison of climate zones, whereas GTI looks at total radiation that a surface receives (Solargis, n.d).

4.2. **Lights Specifications**

To replicate the sun in the laboratory, 8 High-Pressure Sodium lamps are used, which replace sunlight for experimental purposes. The ones used in the experiment are BAY6 600w producing 90,000 lumen output. Which dividing 90000/600 will equal 150 that would be the luminous efficacy 150 lum/w. These lights last more than 12000 hours, making it suitable for the experiment.

Figure 11- HPS lamp (Hydroponics, n.d.)

The reflector manufactured using highly polished, dimpled anodised aluminium and their aim is to maximise light efficiency.

Figure 12- Configuration of lights

4.3. **Solar Thermal**

Solar energy is abundantly available in many parts of the world. It plays a major role as an alternative energy resource. Using the sun's energy can produce heat or electricity by capturing the radiation of the sun. Solar thermal devices convert solar radiation into heat (Tripanagnostopoulos,2012).

For the design of the solar powered pump, a solar thermal collector is used as this device has the focus of collecting solar radiation from the sun. Solar collectors are available in different types, flat plates, evacuated tubes, etc. For this particular design a flat plate collector is selected. They are usually made of metal boxes having a glazing cover along with an absorber plate. Additionally, they are covered with insulation in order to minimise heat losses in the system. Moreover, flat plate collectors are simple and inexpensive (Kalogirou,2009). Attempting to characterise the flat plate collector of the current system, more details are attributed to each individual component. This is done to suggest different materials that might improve the performance of the current system. Figure 13 illustrates how a typical flat plate collector is constructed.

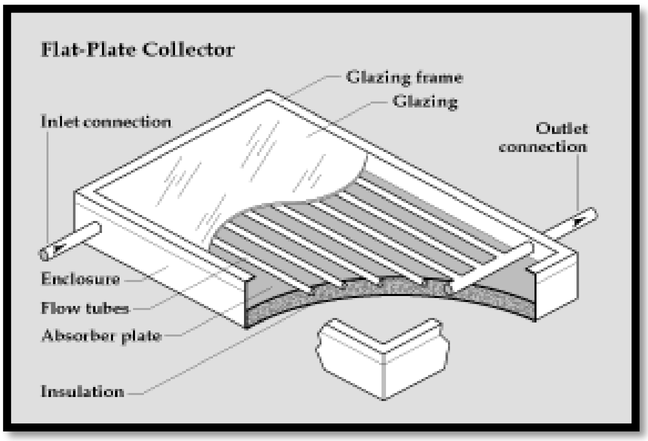

Figure 13- Diagram of a flat plate collector (Wikimedia Commons, 2015)

4.4. **Experimental Solar Collector**

A solar collector containing air is used to maximise the heat collected. Using a simplified version of a commercially available product that uses “TeknoTerm” absorber strips containing 8mm (id) copper tubes. The panel is double glazed with two layers of Teflon film 2 cm apart. It has a side thickness of 10, 2 cm and consists of two base sides in a 45o angle of 46, 8 cm.

The figure below shows the experimental diagram of the solar collector used in Carey’s experiments and it still used today for further analysis.

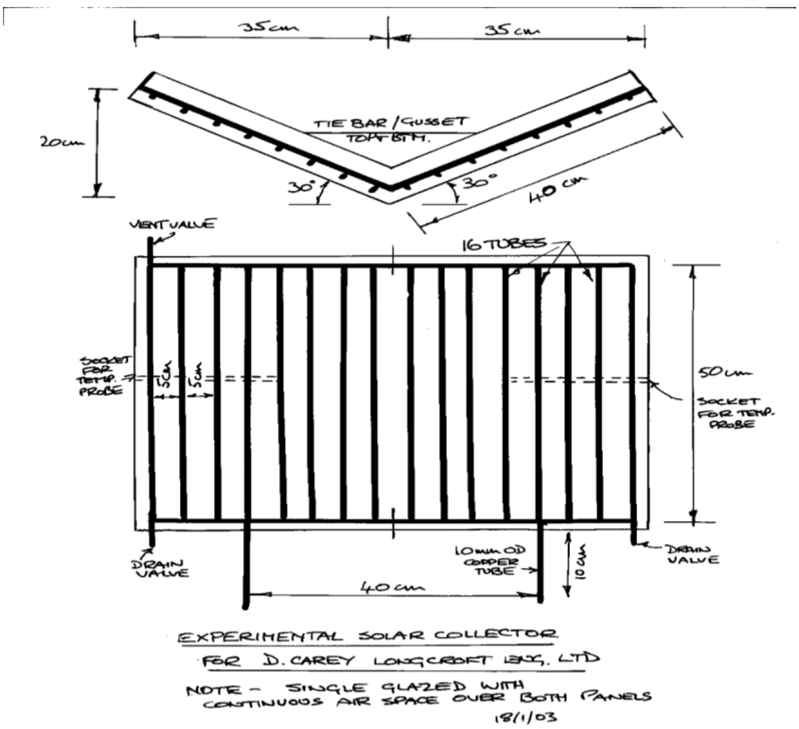

Figure 14- Full diagram of the current flat plate collector (Carey, n.d.)

To note that the diagram above illustrates the collector that is currently being tested along with the resonance pump.

4.5. **Analysis in flat plate collector components**

One of the first recommendations left by Dennis Carey before significant improvement in the performance of the pump was achieved, was to profoundly understand the inner workings of the solar collector. Knowing the reason why this type of collector is used, as it is easy to manufacture and requires little maintenance making it suitable for the desired application is also fundamental, despite the fact that its cost is expensive. A brief description of the collector is made in the previous section, but a full description of all materials used in the collector still not documented, thus in this section a complete analysis of general flat collectors is taken into consideration. This has been done to improve the understanding of the type of collectors that we are dealing with. It is relevant as certain components have such a great impact on the collector performance and this might help to draw certain conclusions and possibilities for a developed system. Analysing different materials available in the market will help me suggest an improved collector in case one is needed.

Glazing Cover

The transparent layer known for transmitting radiation to the absorber is called glazing cover. Having this in the solar collector will prevent radiative and convective heat loss from the surface. Taking into consideration the fact that, collectors glazing is exposed to high temperatures, lengthy outdoor exposure, impacts and requiring a reasonable cost, choosing one should require certain properties. Ideally, a glazing material for this application should have high temperature capability, transmit light, be very impact resistant, easy to work with, and low cost.

Low Iron Tempered Glass which has good transmittance, high temperature capability, and is strong. However, its ease of damage and high cost is a concern when attempting for a good selection. Alternatively, non-tempered glass is also available in the market, though tempered with a low iron content is highly suggested. Non-tempered usually crack from the heat and having high iron will transmit less light. Tempered glass, which is stronger than other types of glass, is considered a 'safety glass' as the glass only shatters in small harmless pieces when it breaks (SINOvoltaics, n.d).

Surface Coating

One of the crucial parts of solar collectors is the surface coating, which enhances the efficiency of solar to thermal energy conversion (Yang,2012). When designing or identifying a collector for purchase, components should be selected effectively. In terms of coating there are two key features that must be considered:

- High absorption >0.95
- Low emissivity < 0.85

The reason for these key features is that surface absorbers should exhibit high absorptance(α) in the solar spectrum (0.3-2.4μm) to capture maximum solar energy, and low emittance(ε) (2.5-20μm) for a reduced energy loss (Yang,2012).

Jordan (n.d) states that there are two types of coating techniques: non-selective and selective coatings.

Table 2- Coating techniques

Non-selective coating technique	Selective coating technique
High absorptance	High absorptance
High emittance	Low emittance

From the comparisons illustrated above, selective coatings are ideal as their features correspond to what is expected for good absorbers. Also, selective coatings that will not degrade in terms of optical properties during their lifetime and they can withstand stagnation temperature (Tesfamichael, 2000).

The use of paints is ideal, as they are less expensive, and a positive side is that they can be produced by simpler methods. For instance, Black Nickel and Black Chrome. They have high absorptivity and low emittance. Black Chrome has its cost relatively low compared to nonselective coatings (Nahar, 1981). It is durable, resistant to humidity and extreme temperatures making it suitable for this application.

Insulation

The use of solar thermal insulation will minimise heat loss, and will also prevent the material from overheating, which optimises the efficiency of the collector (Khaw W et al., 2015). A good insulation should deliver minimal heat loss, have good thermal stability, long useful life and be cost effective (Rabe et al., 1981). A study has been conducted done where insulating a frame with fibreglass and results have shown the effect of applying coconut coir/ fiber. This has shown to have a great effect compared to polypropylene insulators. They showed that insulating the frame using coconut coir it is 13.7% higher in terms of efficiency (Khaw W et al., 2015).

Conclusion

The attempt here was to easily describe materials available in the market and give an alternative solution for the future when improving the collector. The conclusions driven here are not experimentally tested but they are based on materials specifications, cost, durability, and characteristics performance. The attempt is to design a collector that can be designed with cheap materials in rural areas, but also see if they would make a difference in the performance of the collector.

A suggestion is to use coconut coir/ fiber when insulating the frame. Such natural materials are available in Sub-Saharan Africa and are ideal since they are more environmentally friendly (Ebohon & Rwelamila, n.d.). To note that is convenient to use easily available materials. Regarding the transparent cover, a low iron tempered glass is suggested as it contains desirable properties. For the selective coating surface, black chrome can withstand high temperature, and it combines high absorptance for radiation with low emittance making it a greater option.

4.6. **Pump**

Description

Simple arrangement of metal tubing. A ‘U-shaped’ copper tube is used to form a closed loop as mentioned before. The lower pumping unit can be built from domestic copper tubing using soldered or compression fittings. The tubes are to be submerged in water to a determined depth.

Three pumps were used alongside the experiments and to note that all of them are experimental lab scaled pumps as a working model, used to prove the concept of the design. Once this is completed the pump will need to be scaled to a larger size for the real application. Thus, the point of working with this size is to understand the parameters and its functioning. **Pump 1** is one of the originals designed by Carey in the early 2000s. It has since brought to the university and used for experimental purposes only. **Pump 2** was designed as an attempt to monitor the movement of the water, therefore the glass tube was added, where same dimensioning is applied from the original pump. **Pump 3** is a more instrumented version designed to carry the experiments with sensor connections with the same dimensions as the original design.

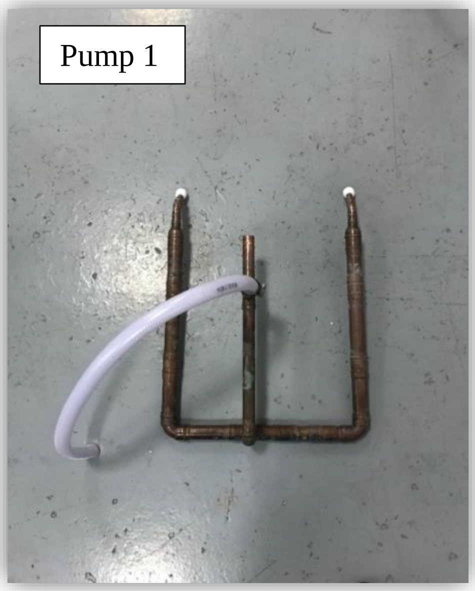

Figure 15- Original pump and adapted design with clear glass tube

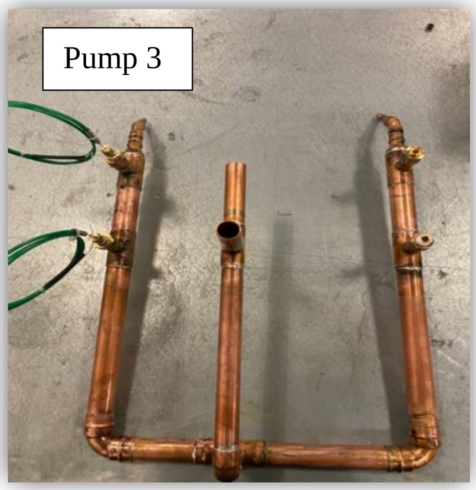

Figure 16- Designed pump

Geometrical parameters

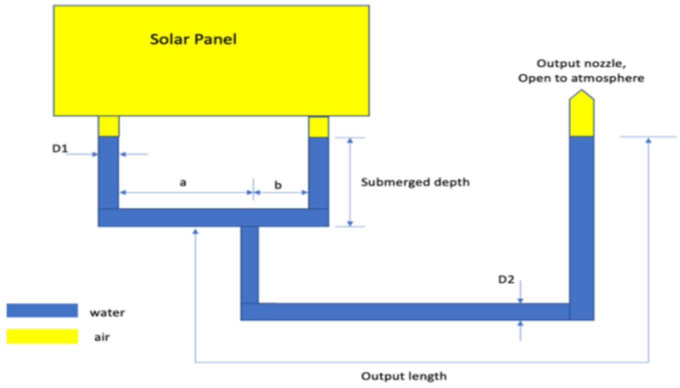

Figure 17- A schematic diagram of Carey's pump (Khodabakhshi, n.d.)

The diagram above illustrated will indicate the geometrical dimensions used in the original and designed pumps, giving a description of the pumps.

Table 3- Geometrical parameters of the pump.

D1	26mm
D2	20mm
a	215mm
b	145mm
Pm	10^5 Pa
ρ	1000 kg/m^3
Vm	640 cm^3

To note that the submerged depth varies in arrangement of 0.15-0.4m due to the capacity of the tank and output length in the range of 0.15-4m.

From previous work, the key parameters were found by estimating the submerged depth according to the size of the tank. In addition, the output length was found through a resonance approach. In this method, Luis (2019) tried to maximise the output amplitude through size selection and as a result the parameters were found.

When setting a submerged depth value, the total length is estimated allowing the value of the natural frequency of the ‘U-tube’ to be calculated. This given frequency will then be used to find the value of output length by approximating the natural frequency of the 'U-tube' with the output tube.

4.7. **Water tank capacity**

The water tank in use has a capacity of approximately 350l.

Table 4- Water tank capacity

Measurement	**Metric (mm)**
Length	953
Width	660
Height	535

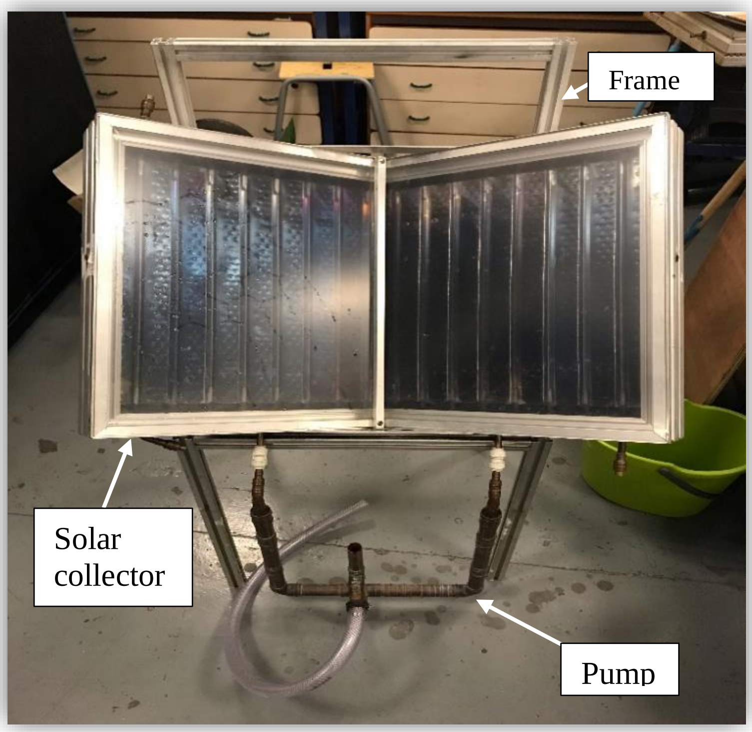

Figure 18- Whole system ready to be placed in the test rig

Chapter 5: System Operation

Dennis Carey proposed the design believing that the system operation was based on a Fluidyne engine, therefore its calculations were designed accordingly. Notably, at the time he did not instruct it. The design has been instrumented now and more attention in the operating principle is being questioned following with better understanding.

From what has been proposed by Carey, the system operates as a simple form of hot air engine using pistons to pump water with no moving parts (Carey, n.d). The pipe should be partially submerged into a reservoir of cold water. The hot end which accounts the solar collector which contains air initially at atmospheric pressure and temperature. The cold end contains water. Heat transfer happens from the solar collector raising the air temperature inside the closed loop, the pressure rises and expands by pressing down on the water in the lower half of the loop.

When a difference in temperature between the hot and cold side reaches a certain temperature, the water column starts to oscillate. If an inlet and outlet tube are connected to the lower submerged end of the loop, a pulsating outflow of water will be created.

5.1. **Resonance approach**

Different attempts to describe why the system works in that way have been made in the past years. Previous studies have placed emphasis on the thermodynamic model of the design to analyse the mode of operation resulting in an assumption that the system worked according to a resonance approach where natural frequencies of the 'U-tube' and the tuning length had to be equal in order to observe oscillations in the system. Although it was possible to prove this statement and results have also supported this finding, it is not sufficient to clarify the thoughts regarding its principle of fundamentals. It is needed more and therefore, further investigation was carried, and other possibilities attempt for a clarified explanation.

A theoretical model was being used to optimise the performance showing the relationship between the resonance tube length and performance. Notably, to observe resonance in the system the natural frequency of the water oscillating in the 'U-tube' needs to be equal to the water column oscillating in the output tube. The theory relies on analysing a resonance model where a combination of two water column vibrations cause oscillation. In order to observe resonance conditions, the natural frequency of the water oscillating in the 'U-tube' must be equal to the frequency of the water column oscillating in the output tube.

For any particular body in a condition of simple harmonic motion:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{2g}{Ld}} \qquad (1)$$

$Ld = (submerged\ depth * 2)$ + a + b

An equation of motion of the output column is considered that can lead to temperature difference to initiate oscillations. From deriving the equation, the liquid in the output columns at its natural frequency is given by:

$$\omega t = \sqrt{\frac{\left(\frac{P_O At}{\rho Vm}\right) + g(1+\frac{A}{2})}{Lt + AH/2}} \qquad (2)$$

In his 1983 article, West indicated that in practical machines the gas gives a greater restoring force compared to the gravity, and the total length of the output pipe is greater than the length of the upright's displacer neglecting gravity forces and H, leading the equation to:

$$\omega t = \sqrt{\frac{P_O At}{\rho VmLt}} \qquad (3)$$

The following equation was used to obtain the frequency in the output tube which was used by Khodabakhshi (n.d) in his report. By combining equations 2 and 3, the frequency in the water column oscillates in the output.

$$f = \frac{1}{2\pi}\sqrt{\frac{Pm*At}{\rho*Vm*Lt} + \frac{\left(1+\frac{At}{2Ad}\right)g}{Lt}} \qquad (4)$$

These formulas were used by Luis (2019) to compute frequencies and find the exact parameters so that the pump could work accordingly.

Procedure

To start, the value of the submerged depth is used to calculate the total length (Ld), then the natural frequency in the u-tube is calculated.

$$Ld = (0.3 * 2) + 0.215 + 0.145 = 0.96\text{m}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{2*9.81}{0.96}} = 0.719 \sim 0.72 \text{ Hz}$$

Table 5- Data collected from the water column oscillating in the u-tube pipe.

Submerged depth	a	b	Ld (total length)	g	Natural frequency
m	m	m	m	m^2/s	Hz
0.2	0.215	0.145	0.76	9.81	0.808
0.24	0.215	0.145	0.84	9.81	0.768
0.3	0.215	0.145	0.96	9.81	0.719
0.34	0.215	0.145	1.04	9.81	0.691

The value of the natural frequency is then used to observe a similar value in the frequency of the output tube and then estimate the value of the output length to use in the lab for experimental purposes.

Table 6- Data collected from the water oscillating in the output tube

Pm	At	Ad	ρ	Vm	Output length	g	Frequency Output tube
Pa	m^2	m^2	Kg/m^3	cm^3	m	m^2/s	Hz
10^5	0.000314	0.000531	1000	640	0.5	9.81	0.746
10^5	0.000314	0.000531	1000	640	0.6	9.81	0.721
10^5	0.000314	0.000531	1000	640	0.7	9.81	0.694

$$f = \frac{1}{2\pi}\sqrt{\frac{1000*0.000314}{1000*640*0.6} + \frac{\left(1+\frac{0.000314}{2*0.000531}\right)9.81}{0.6}} = 0.721 \sim 0.72 \text{ Hz}$$

The initial idea was to understand why the system was not operating with the same parameters that it used in the Dennis Carey observations. From trying to model using MATLAB the observations were inconclusive and therefore the resonance approach was tried.
With this method, a successful result was obtained as the pump started to work. This was possible when combining a submerged depth of 0.3m that had a frequency of 0.72 Hz with the relationship between the output length and frequency, showing that an output length for the frequency of 0.72 Hz is 0.6m.

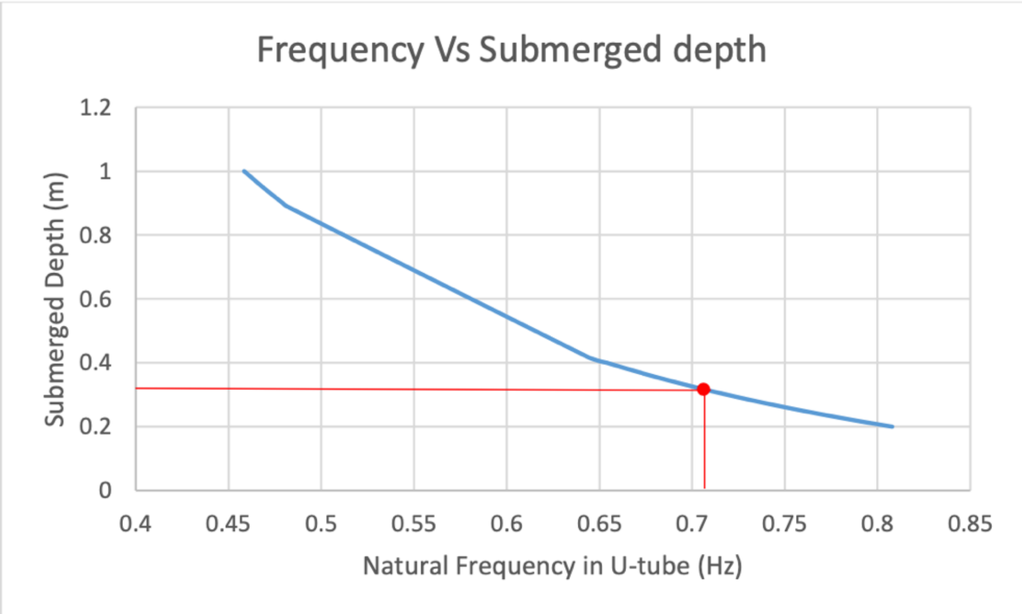

Figure 19- Submerged depth against frequency in the U-tube (Luis,2019)

Having found the output length from this relationship, tests were done in the lab, and finally observations from water coming out to the atmosphere were also achieved.

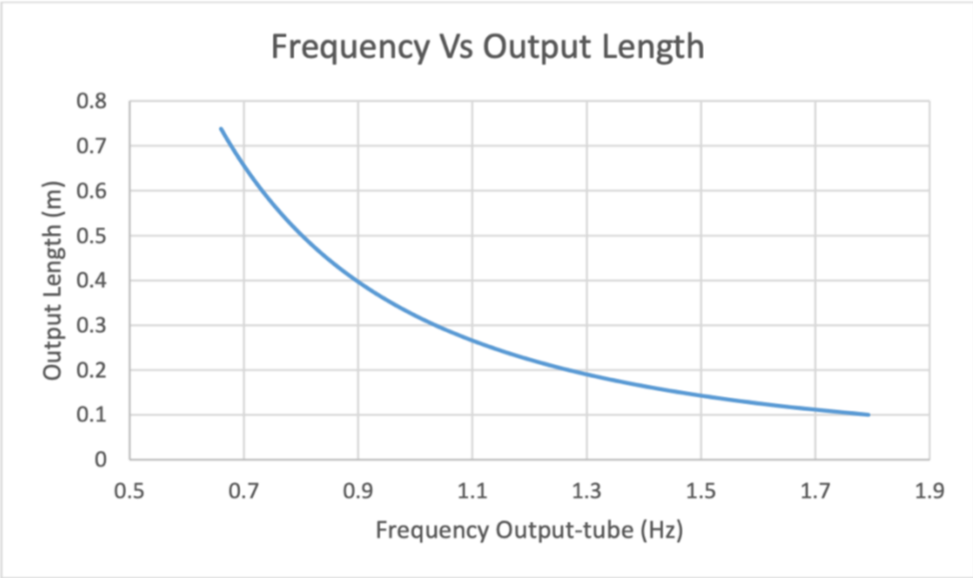

Figure 20- Tunning length versus natural frequency in the output tube (Luis,2019)

From this method, a resonance is seen to occur in the system, and it is believed that a phase angle between oscillations in the columns should be 90 degrees. From these results, Luis (2019) concludes that by matching the natural frequency in the U-tube with the frequency in the output tube the system works in resonance, and this gives values for the submerged depth and the output length of the system. In addition, from the formulas used in the approach it was possible to observe that frequency is inversely proportional to the length.

By applying the combination of a submerged depth of 0.3m and tuning length of 0.6m found from the modelling, as a result the system started to work at a temperature of 90 degrees and water was observed coming out of the pump as illustrated in figure 21.

In the output frequency calculation, the output length was the only variable that was not fixed. Showing a relationship of frequency and length meaning that frequency is inversely proportional to resonating length, thus, the amplitude takes longer to cross the equilibrium.

$$\boldsymbol{f \propto \frac{1}{L}}$$

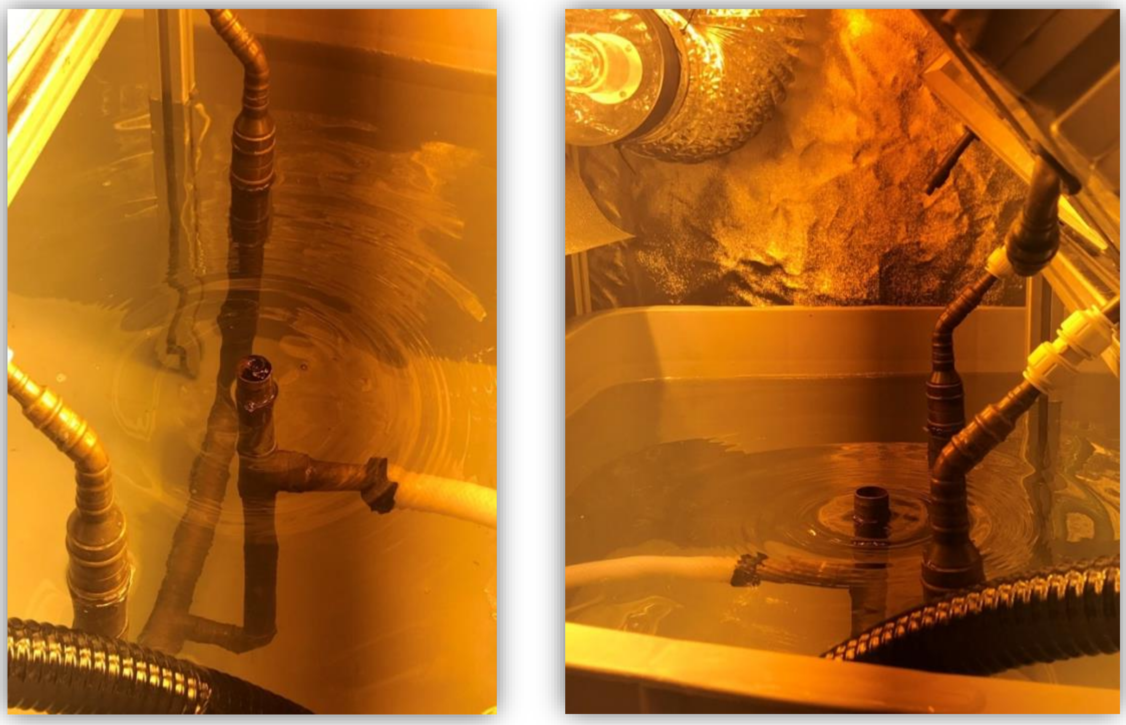

Figure 21- Experimental observations.

Chapter 6: Research Results and Discussion

With the purpose of characterising the system, pressure fluctuation was analysed to understand the inner workings of the pump as the entire system can be affected by inconsistent water pressure or analyse if there is an issue with the pipes.

6.1. **Pressure fluctuation**

Pressure and temperature sensors are set in the configuration of the new ‘U-tube’. Pressure was measured on both sides of the ‘U-tube’. Temperature measures where the hot and cold side meets. In this report, P1 is referred to the arm of the ‘U-tube’ where thermocouples are placed, whereas P2 is located on the other side arm. It took approximately 90 minutes to run this experiment where pressure and temperature data were recorded using a picoscope.

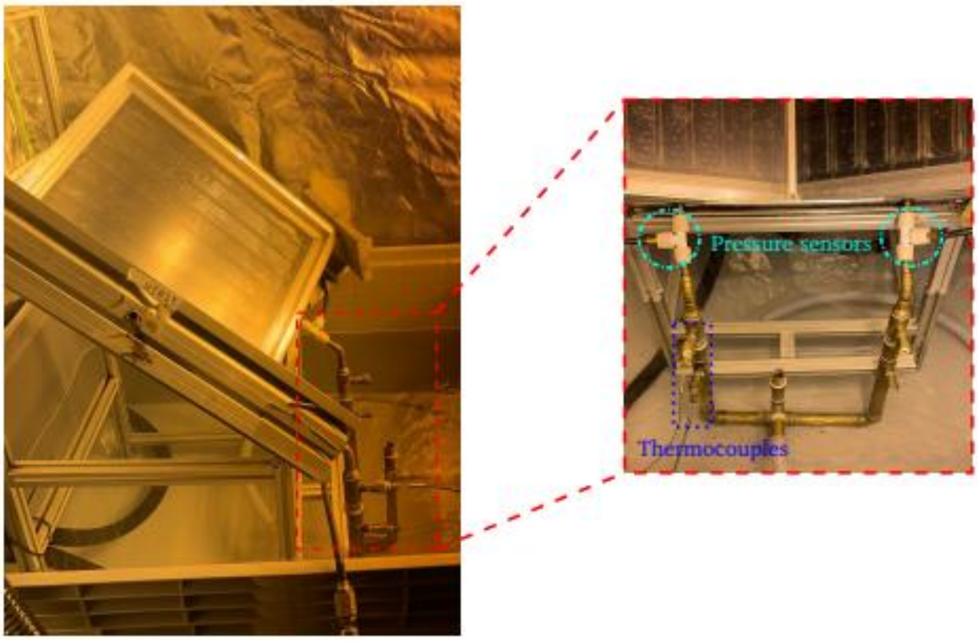

Figure 22- Sensor's indicators

The following figures show measured signals of voltage and calibrated values of pressure and temperature. The pressure is seen to increase to 24 mbar and decrease afterwards at the expense of pressure fluctuations as observed in figure 24.

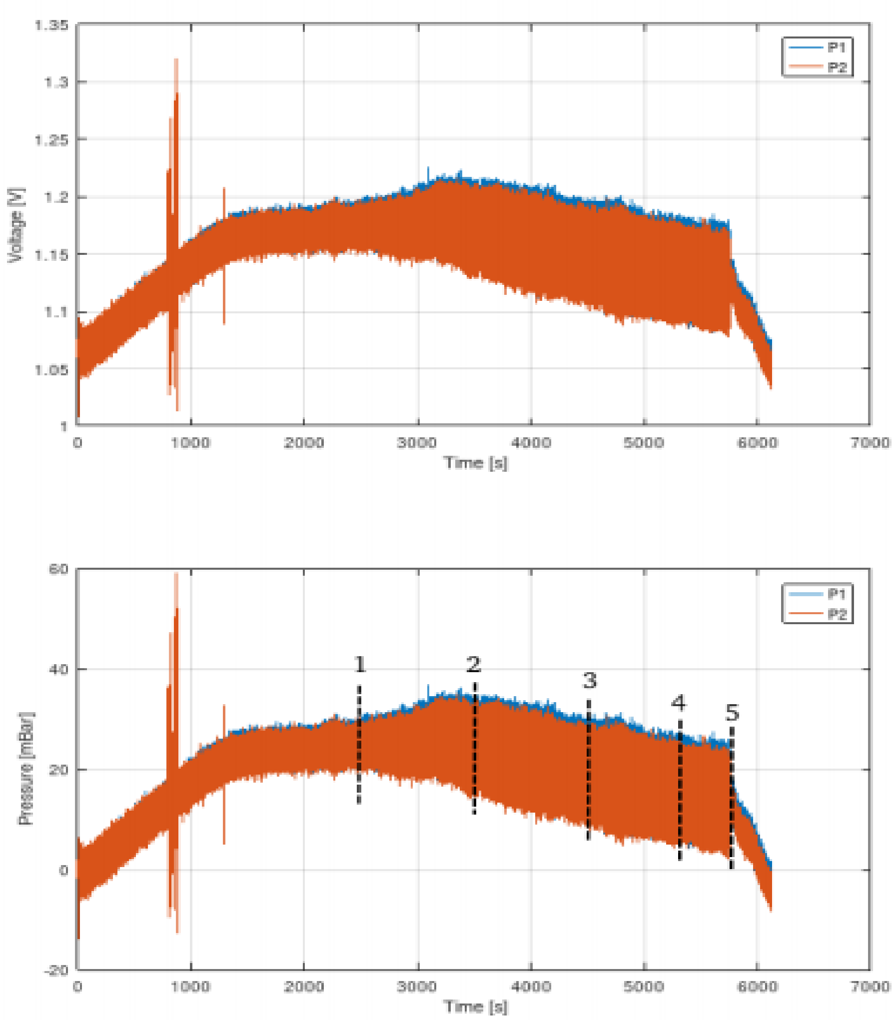

Figure 23- Evolution of gauge pressure at the specified locations

In Fig24 pressure is shown with five points that leads to analyse pressure fluctuations. To note that point ‘5’ marks the time when the lamps were powered off.

Some unauthentic data seems to be visible around 940s, where some vertical lines are clearly observed from P2 only. The system is observed to maintain itself at a negative gauge pressure once the heat input is taken away.

The temperature differences of about 10 ◦C are observed between hot and cold junctions from fig25. Furthermore, an overall increase in the temperature of the cold junction is observed with time and this is expected to be caused by an increase in the temperature of the tank as it cannot behave as a perfect sink due to the limited size.

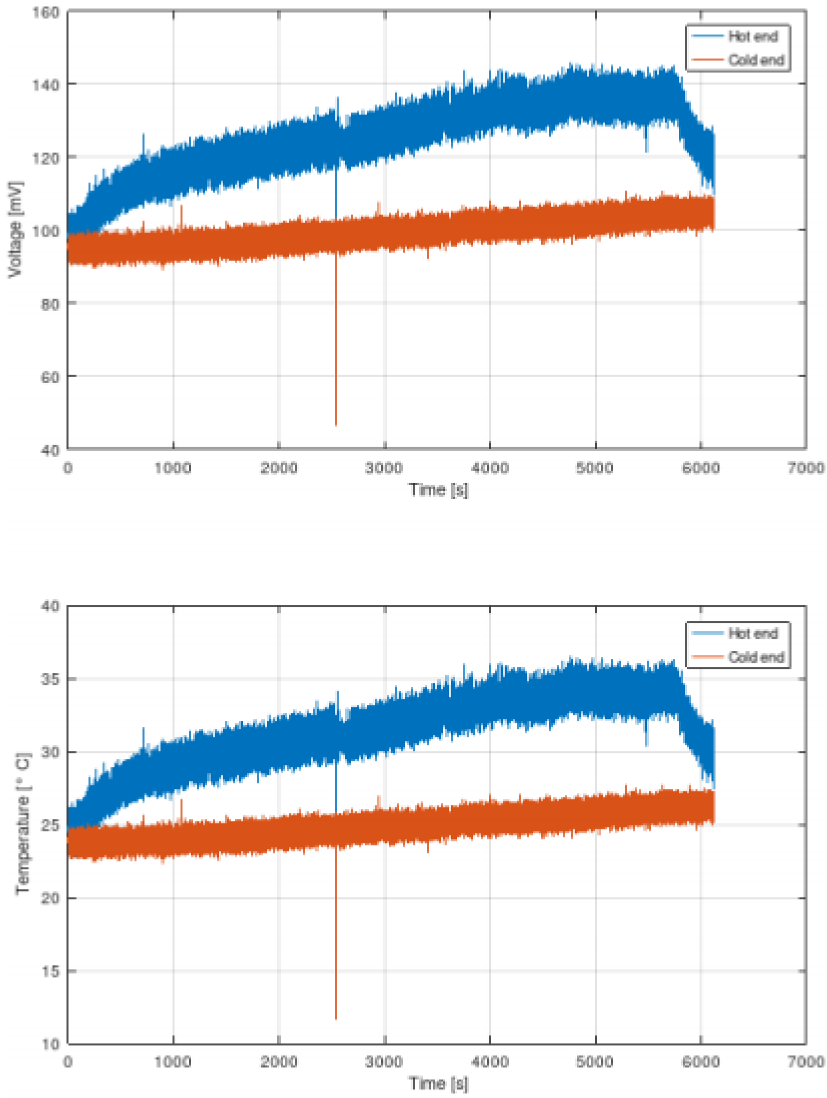

Figure 24- Evolution of temperature

The onset of the fluctuations can be observed at 2500 s (section 1). These fluctuations become apparent with an increase in the amplitude at 3500 s (section 2). The amplitude of these fluctuations is further increased to 15 mbar at 4500 s (section 2) while the mean of these fluctuations is observed to drop from 22.5 mbar at section 2 to 20.5 mbar at section 3. The amplitude of the fluctuations does not increase after 3500 s but a further decrease in the mean of pressure fluctuations (to ≈17.5 mbar) is observed in section 4. Additionally, the pressure fluctuations at the two arms of the pump were observed to be in phase. It is worth pointing out that the mean of the pressure fluctuations was still decreasing and therefore, a longer duration is required to measure the steady operation of the pump.

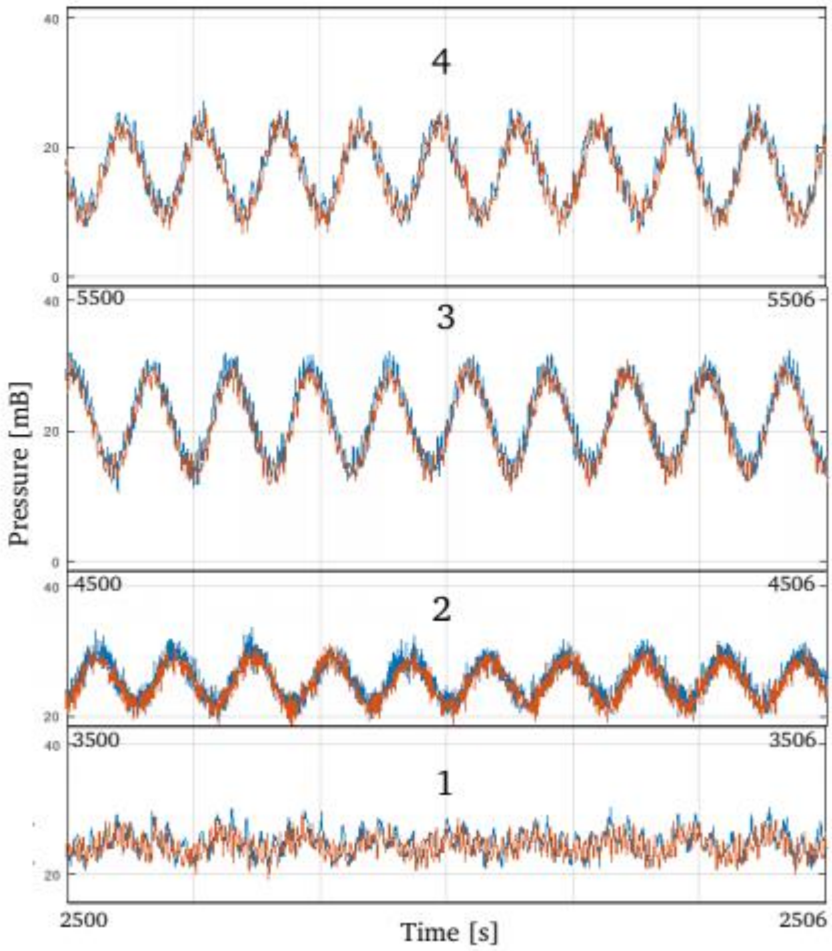

Figure 25- Pressure fluctuations

From the results shown above, a drop in pressure is observed that could indicate a possible leak in the system.

Notably, the system cools down and a decrease in pressure happens, along with a difference in temperature drops. A suggestion of having a valve that opens in a certain temperature to control the pressure and maintain it throughout the operation may solve this issue. Suggestions from Carey using a valve that opens at a predetermined temperature and permits hot air to flow into the cold air space was once tested, and consequently removed from his experiments. An alternative testing method could involve re-inserting the valve and observing to see if it has positive effects in experiments.

6.2. **System operation principles**

From a discussion with a University in Japan, theory of the system was discussed, and an exchange of information led to questions that relate concepts of a standing-wave and travelling wave engine. This discussion led to questioning whether Carey's engine is linked to the Fluidyne (traveling wave engine) or the Huelsz's engine (standing wave engine). This might raise a contradiction to what has been discussed throughout the report, therefore it should be investigated for further understanding. This can be achieved by relating standing wave and travelling wave engines to the concepts of a Fluidyne engine, to verify which concept relates to the model used.

Suggestions were made to help identify which concept Carey's engine belongs to, using the frequencies f0 and f. If the oscillation frequency of the Carey's engine is close to f0, it should be considered as a Fluidyne engine. If the frequency is close to f, then it should be related to Huelsz's engine. In this case, the liquid columns in the 'U-tube' of the Carey's engine should oscillate in phase with equal amplitudes.

This Fluidyne principle is set to operate as out phase, and this has been reported to still hold true. However, the data collected shows the opposite, indicating that the system is operating in phase.

Chapter 7: Conclusion and Recommendations

This research had the purpose to identify the suitability of implementing a solar thermal powered pump in Sub-Saharan Africa, if possible, in Zambia, and to understand the basic principles of the device by researching different principles proposing what principle is the system operating and testing to confirm which one is it at. Based on the analysis provided above, it can be concluded that introducing the solar powered resonance pump offers more advantages to tackle the current situation in Zambia's irrigation sector, as the system requires little maintenance, can be operated without supervision, and meets all clean energy fundamentals. If implemented can contribute to a safer and greater life of farmers. In response to the fundamentals of the solar pump, the results indicate a miscomprehension of the operating principle that Carey was investigating at the time. Consequently, research in this system was only focused on the Fluidyne engine principle, and now with more investigations on the fundamentals it led to possible new concepts, and it is concluded that the solar powered resonance pump could potentially be operating in a putt-putt boat principle.

This research clearly determines a valuable solution of solar thermal collectors for rural areas, underlying the importance of using solar thermal instead of photovoltaic. Notably, photovoltaic pumps are expensive and the conditions prevailing in rural areas do require simple, low maintenance and a system that can be operated without sophisticated technical skills. Thus, the use of a photovoltaic system is not considered for a start. The research also involved characterisation of the current system analysing the power input and the resonance pump to give an understanding of what is happening inside of the solar collector and in the 'U-tube' pipe.

Cyclical pressure variations were observed providing a reasonable understanding of the evolution of pressure and temperature in the 'U-section' of the solar pump. Furthermore, pressure first increases then decreases at the expense of fluctuations. The drop could have indicated a potential leakage happening somewhere in the system, and therefore be the root cause for the drop. Notably, a verification to see if there is any leakage is the first thing to do. More pressure sensors and more observations are certainly required.

From what has been discussed and presented in this report, recommendations for future work are stated as follows:

- Running the test to monitor the cooling down cycle until steady pressure and temperature data can be seen.
- If there is a leak in the system, trace, and seal it.
- Studies on frequency and amplitude of pressure fluctuations should carry on.

Further experimental research is needed to determine what type of engine it is in fact and test the prototype in Sub-Saharan Africa. This, therefore, implies that more testing is required, and a suggestion would be to add water in the solar thermal collector so that the prototype is tested similarly to the putt-putt boat model.

To conclude, the model is still far from being produced in a commercial stage, but it is not far from being scaled for testing in Sub-Saharan Africa. However, there are specific needs that require testing to fully understand the physics involved. Once further research is completed, the solar thermal powered pump may help to improve productivity and socio-economic conditions in rural areas.

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