Sustainable Energy Solutions for Irrigation and Harvesting in Developing Countries

Thesis by

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For my family

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Abstract

One of the critical problems currently being faced by agriculture industry in developing nations is the alarming rate of groundwater depletion. Irrigation accounts for over 70% of the total groundwater withdrawn everyday. Compounding this issue is the use of polluting diesel generators to pump groundwater for irrigation. This has made irrigation not only the biggest consumer of groundwater but also one of the major contributors to green house gases. The aim of this thesis is to present a solution to the energy-water nexus. To make agriculture less dependent on fossil fuels, the use of a solar-powered Stirling engine as the power generator for on-farm energy needs is discussed. The Stirling cycle is revisited and practical and ideal Stirling cycles are compared. Based on agricultural needs and financial constraints faced by farmers in developing countries, the use of a Fresnel lens as a solar-concentrator and a Beta-type Stirling engine unit is suggested for sustainable power generation on the farms. To reduce the groundwater consumption and to make irrigation more sustainable, the conceptual idea of using a Stirling engine in drip irrigation is presented. To tackle the shortage of over 37 million tonnes of cold-storage in India, the idea of cost-effective solar-powered on-farm cold storage unit is discussed.

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Chapter 1

Introduction

1.1 Motivation

Agriculture requires the use of fresh water to irrigate crops. On Earth, 2.5% of the total global water is the fresh water, 68.6% of which is in form of glaciers and ice caps, 30% lies under the ground in rock fractures and soil pores, and remaining 1.4% lies over the surface in form of rivers and lakes [1]. Groundwater forms a major source of fresh water for agricultural uses [2–5].

India and China inhabit about 37% of the world's population [6], but have only 9% of the world's groundwater resources [2]. In China, groundwater is used to irrigate more than 40% of the total arable land and to supply 70% of drinking water [7]. India alone accounts for over 56.1% of global ground water withdrawal for irrigation every year [8]. Figure 1.1 shows the annual water consumption for irrigation in India and China along with other groundwater consuming countries [9].

Increasing human population and inefficient surface water irrigation system has forced the farmers in developing countries to use groundwater as a major source for irrigation [10–14]. Even though groundwater is considered a renewable resource [1], its over pumping for irrigation needs has caused it to deplete at a rate which is much higher than the rate at which it could be replenished. In the densely populated regions of India, China and South East Asia, the farmers are now facing an imminent threat due to the receding groundwater levels [12, 15, 16].

In developing countries, the energy to pump the groundwater primarily comes

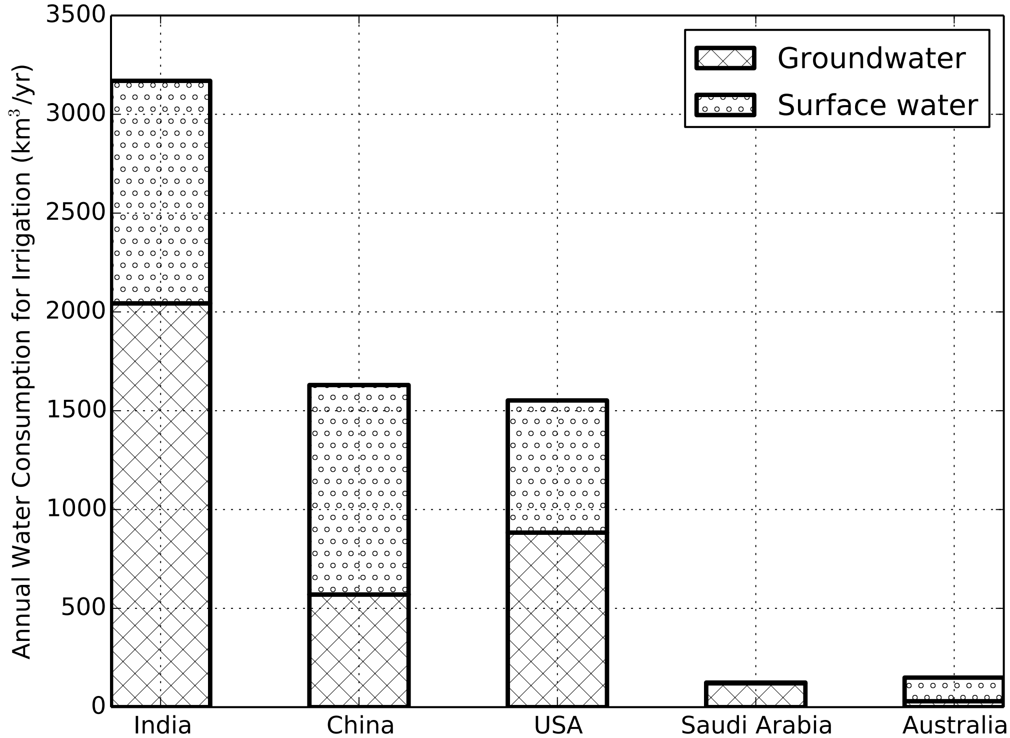


Figure 1.1: Annual water consumption for irrigation in selected countries.
Source: IGRAC GGIS

by operating a water pump [5, 11–13, 17]. Figure 1.2 shows the changing landscape of the sources of irrigation in India. In 2010, over 60% of the net irrigated area in India was irrigated by groundwater which was pumped by using electric and diesel pumps [8]. Since the electricity generation in developing countries primarily comes from burning fossil fuels (e.g.: coal) [18], it is safe to conclude that pumping the groundwater contributes to green house emissions. Both fossil fuel power plants and diesel generator exhausts contains high amounts of green house gases [18, 19]. Several on-farm studies done by Shah et al. and United Nations Water have concluded that groundwater irrigation is the most energy consuming operation on the farm. [4, 11–13, 17, 20].

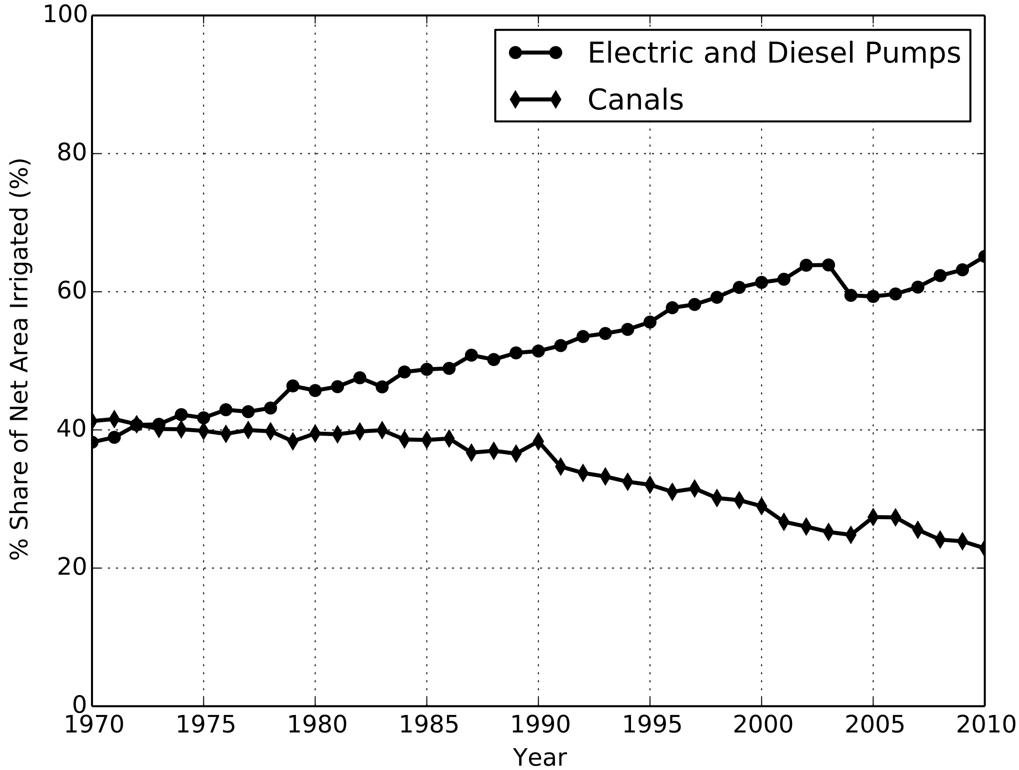


Figure 1.2: The percentage of net area irrigated by irrigation source in India.
Source: CMIE

1.2 Research Objectives

The objective of this thesis is to propose one of the solution which would make groundwater pumping sustainable and help reduce the groundwater consumption. Specifically, this thesis discusses the feasibility of using solar energy to operate water pumps by way of using a Stirling generator. It provides the design elements for a solar-powered Stirling generator and discuss its applications for two on-farm operations: (a) as a water pump for usage in drip irrigation system (b) as a generator to drive the compressor in a portable cold-storage system. The drip irrigation technology has been in existence since 1920 and is one of the efficient ways to limit the water consumption in irrigation [21–23].

This thesis is also intended to provide a review of Stirling engine and the associated design challenges. The discussion aims to provide the current state-of-art in Stirling engine technology and can be loosely used as a guideline for a conceptual design of a system which wishes to use Stirling engine as one of its component. The Stirling engine, by way of its design, can convert thermal energy into mechanical energy and hence its application is not limited to use of solar energy but also other renewable energy sources like bio-diesel, rice pellets etc.

1.3 Scope of the Study

As mentioned earlier that the goal of this thesis is to discuss the idea of using a solar-powered Stirling water pump as a way to pump groundwater sustainably. While the goal seems simple to state, this thesis can be extremely wide if the scope is not limited. The reason for this is because both Stirling engine design and harnessing renewable energy are two separate problems and are topics of active research. The characteristics of each could result in numerous permutations each solving the issue of groundwater pumping. For example, one could use photovoltaic to harness solar energy and use it directly to operate a water pump. Alternatively, in areas with high wind potential, wind turbines could be used to generate electricity to operate a water pump. The solutions presented in this thesis are aimed towards developing countries like India and China, both of which have a high solar insolation justifying the use of solar energy. The case for the use of Stirling generator over photovoltaic is discussed in Chapter 2. It is not obvious a priori to favor the use of photovoltaic over Stirling generator as a way to convert solar energy into electrical energy for the on-farm applications. While photovoltaics have been successfully used in deserts (e.g.: Solar power plants in Mojave Desert) and in urban areas (e.g.: roof-top of the buildings), Stirling engines have found applications as a power module for submarines (e.g.: Gotland-class submarine with Stirling air-independent propulsion) and are topic of active research at NASA for a possible power source for the next lunar habitat.

The issue of rapid groundwater depletion is also extremely wide. While UN has regarded access to safe drinking water as a human right [24], it remains unclear on its stand over the issue of access to the groundwater. There have been numerous studies which suggest guidelines to regulate groundwater usage [25–27], the issue of groundwater depletion in this thesis is discussed from a technological point of view. The idea of using a solar-powered Stirling engine with the efficient drip irrigation system is discussed.

1.4 Thesis Outline

This thesis is divided into five chapters. The description of each is as follows:

Chapter 1 In this chapter, the underlying issues that serve as a motivation for this thesis are presented. The research objectives and the scope of the current study are also explained.

Chapter 2 This chapter presents a brief overview on groundwater depletion and the energy-water nexus. This chapter also provides a review of existing methodologies used by farmers in developing countries, and provides a justification for the use of solar power and Stirling engine as a way to operate water pumps.

Chapter 3 This chapter presents the overview on Stirling cycle, the associated theory, real-world considerations and current state-of-art in Stirling technology. The discussions in this chapter serve as guidelines for various engineering decisions made for the proposed solar-powered Stirling generator.

Chapter 4 In this chapter the conceptual design of the solar-powered Stirling generator is described. The rationale for choosing a beta-type Stirling engine, fresnel lens as solar concentrator and molten alkali metals for thermal storage is presented. It also describes the use of a Stirling engine in conjunction with drip irrigation and to power a compressor for an on-farm cold storage unit.

Chapter 5 In this chapter, the summary of all findings is reported. The outlook for future directions in this research area is also provided.

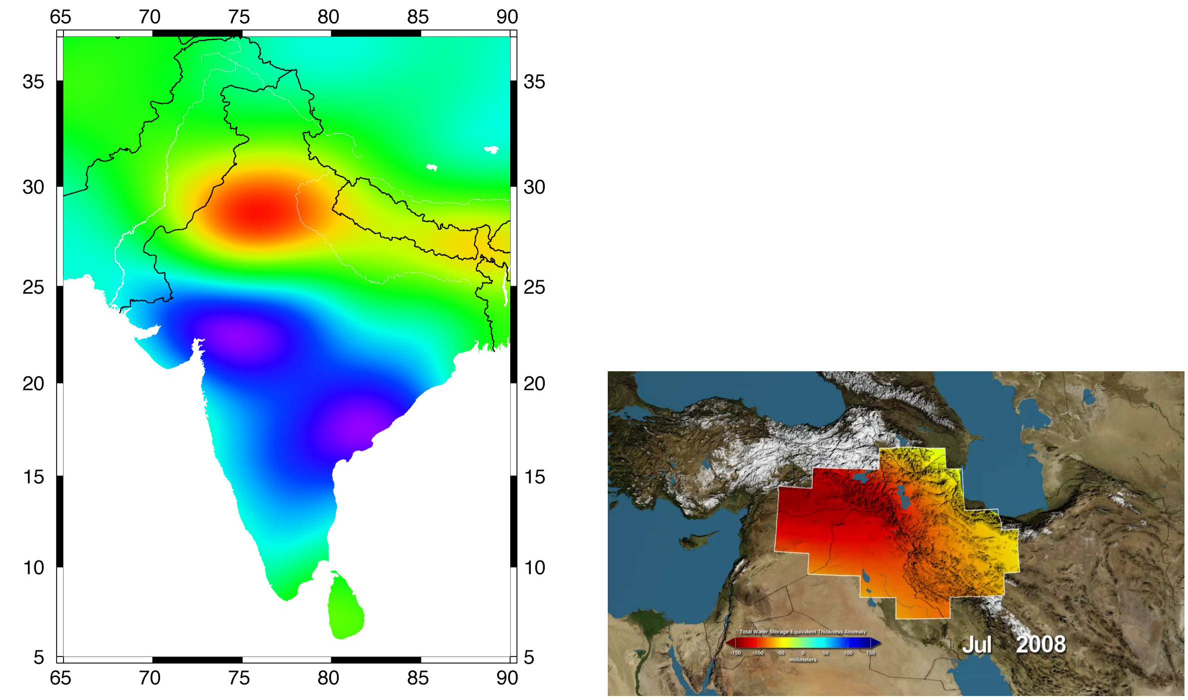
Chapter 2

Groundwater Depletion and Current State of Irrigation

2.1 Groundwater Depletion

Look, water has been a resource that has been plentiful. But now weve got climate change, weve got population growth, weve got widespread groundwater contamination, weve got satellites showing us we are depleting some of this stuff. I think weve taken it for granted, and we are probably not able to do that any more . (Dr. James S. Famiglietti in an interview to New York Times [28])

The above quote succinctly describes the essence of the problem. Groundwater is the predominant source of irrigation around the world, especially in India (39 million ha), China (19 million ha) and USA (17 million ha) [10]. To give a perspective on water usage in the agriculture: producing 1 pound of grain requires about 200 gallons of fresh water while our power plants consume on an average of 143 billion gallons of fresh water every day to produce energy. As the population is increasing, so is the demand of food, energy and hence fresh water. The importance of groundwater to irrigation is similar to that of gasoline for driving automobiles, both must be replenished or refilled from time to time. However, recent measurements of groundwater levels by the NASA's Gravity Recovery and Climate Experiment (GRACE) show that many states in northern India have been losing water at a mean rate of 4.0 ± 1.0 cm yr^{-1} equivalent height of water (17.7 ± 4.5 km^3 yr^{-1}) [15, 16]. Figure 2.1 shows a plot from the GRACE mission showing groundwater depletion in parts of India and Middle East.



(a) India (b) Middle East

Figure 2.1: Groundwater changes in India (during 2002-2008) and Middle East (during 2003-2009) with losses in red and gains in blue, based on GRACE [15] satellite observations.

Image courtesy: NASA JPL

The reason why a farmer prefers groundwater over surface water (e.g.: canals, ponds etc) for irrigation is because it is readily available on site and is a free unregulated natural resource [4, 14, 29]. It is also less prone to pollution than surface water [10]. Since groundwater is naturally recharged by rainwater and snow, the lack of efficient infrastructure to capture the rain water during rainy season (e.g.: monsoon in South Asia, plum rain in China etc.) also contributes to the depletion of groundwater.

2.2 Perspective on Energy Consumption in Agriculture: Energy-Water Nexus

One of the key challenges faced by India and China is that of making irrigation less dependent on energy and to invest in technologies which lead to efficient use of groundwater in irrigation. Figure 2.2 shows the growth in non-renewable energy consumption by agriculture over the last three decades.

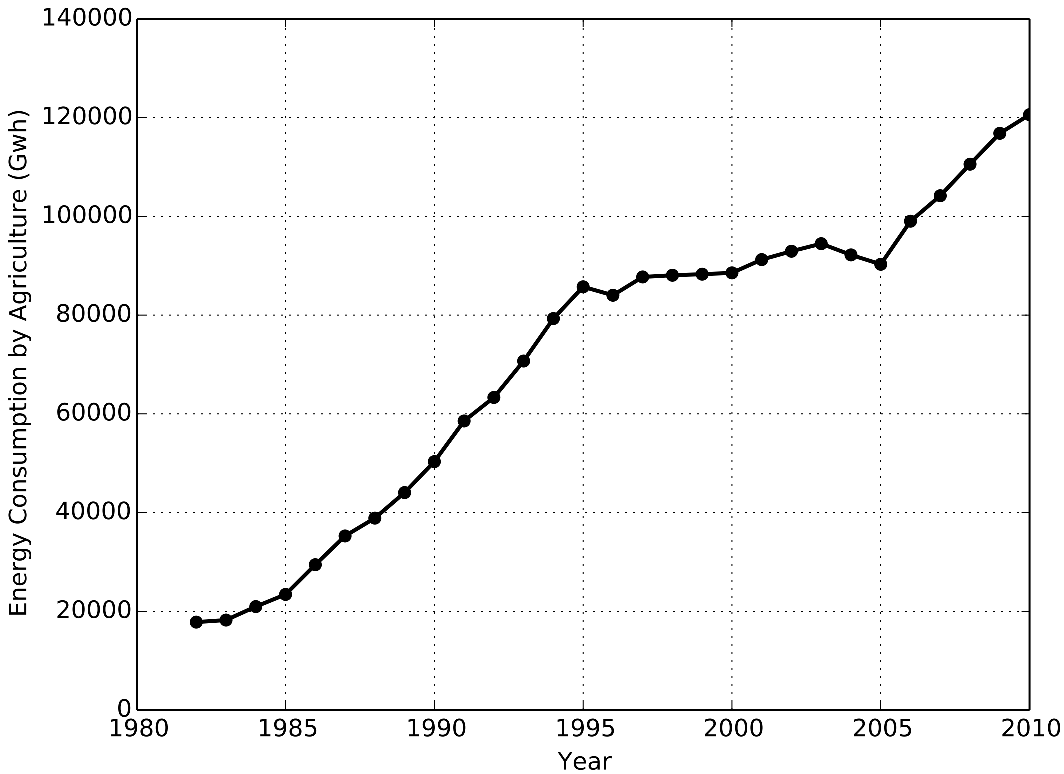


Figure 2.2: Non-renewable energy consumption in agricultural operations in India. Source: CMIE

The most recent data published by the Centre for Monitoring Indian Economy (CMIE) [8] on agriculture and irrigation estimates about 8.0 million electric powered water pumps and about 5.0 million water pumps running on diesel to irrigate 54,500 hectares of land in India. A typical electric powered water pumping system uses a

10 hp horsepower submersible or turbine pump to pull water from about 350 ft with a flow rate of 75 gpm at 75% pump efficiency running for about 6 hours a day [13]. Back of the envelope calculations using these numbers estimate about 350 Gw-hr electricity consumption per day. That is enough electricity to power 30,000 homes in US for one year.

Similarly, a typical farmer in northern India runs a 4 hp diesel powered water pump for about 8 hours to pull water from 150 ft with a flow rate of 75 gpm at 75% pump efficiency [13]. A typical diesel engines used for irrigation purposes in India is about 20% efficient [13, 14] and since gallon of diesel is capable of providing 54.5 hp-hr of energy [30], a farmer is consuming approximately 3 gallons of diesel per day!. Thus, the CO_2 emissions from running diesel engine for irrigation alone is about 54.5 millions of metric tonnes of carbon dioxide ($MMtCO_2e$) per year or 0.2% of the global CO_2 emissions per year. Thus, irrigation is not only the biggest consumer of groundwater but also one of the major contributor to the Green House Gases (GHG). Adding the GHG contribution of irrigation with industry emissions explains why India and China are one of the most polluted countries in the world.

The above calculations highlight a crucial link between groundwater and energy. At the micro level, the two are interdependent, but at the macro level they could be thought of as two independent problems. Reduction in groundwater depletion would lead to healthier acquifer system and a reduction in sea-level rise, which would help the climate. The excess groundwater doesn't seep back into the ground, instead it evaporates and finally enters the ocean thereby causing rise in global sea-level [31]. The issue of groundwater depletion needs to be tackled at policy level and by promoting micro and drip irrigation techniques. However, the issue of energy consumption in irrigation needs to be addressed by building renewable energy solutions [32]. This will take off the load from the electricity grid as well reduce contribution of green house gases.

2.3 Review of Existing Methodologies Used in Irrigation

Before the green revolution, the canal system was the major source of irrigation in India and China. The flood flows in the major rivers like Ganges, Indus and Yangtze were diverted through inundation canals for irrigation. In the areas where rivers were scarce, water was stored in large tanks for use in agriculture. A farmer would flood his field so as to ensure sufficient supply of water to the crops and to safeguard himself from erratic canal water supplies. However, with advent of green revolution and to meet the ever growing demands for food, groundwater usage started to gain momentum. Over the three decades, the net area irrigated by canal system in India dropped by 18%.

(a) Canal system

(b) Diesel engine used to pump groundwater

Figure 2.3: Typical irrigation systems used in India.
Source: najeebkhan2009 via Flickr Creative Commons

The groundwater irrigation system consists of a water well, power source, water pump, storage tank and a pipeline to distribute water. The most widely used power source has been the subsidized electricity from the public grid. However, with increase in the demand of electricity for domestic and industrial use, farmers have switched to diesel generators to operate the pumps. There have been several pilot projects in India and China which make use of photovoltaic panel to convert solar energy into electricity used to operate the pump. However, no large scale projects, utilizing renewable energy as power source, have been deployed both in India and China. One of the main reasons being lack of willingness by the farmer to use any new technology.

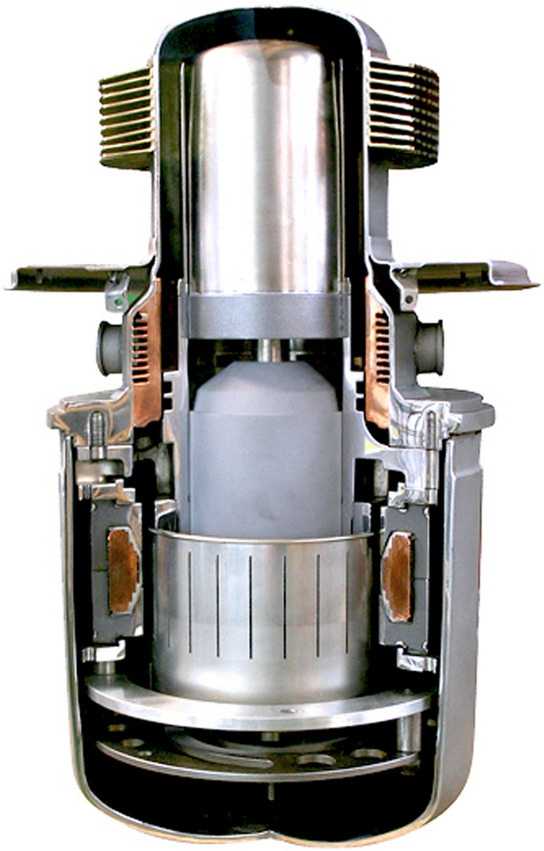
2.4 Renewable Energy Sources for Irrigation

The two promising renewable energy sources which could be used for on-farm application are solar and wind energy. The other possibility could be the use of biofuels instead of diesel in existing generators. However, the production of biofuels require huge amounts of fresh water that may compete directly with food crop production [33]. Table 2.4 summarizes the pros and cons of different power sources for use with groundwater pump.

Since India and China are both located in sun-belt of the Earth [35], its use is preferred over wind and biodiesel as a energy source to power the pump. Within solar, a photovoltaic system enjoys the benefit of lower initial cost when compared with solar-powered Stirling engine. However, its major disadvantage is the system security requirements. The PV array, which are the most expensive components, need to be saved from theft, vandalism and livestock. Sovacool et al. have reported vandalism as the major social barrier to the success of photovoltaic system in rural and on-farm areas [36, 37]. Stirling engine, on the other hand, are immune to vandalism as they are enclosed in a solid metal casing (see fig 2.4) like any other engine. However, when using solar power to operate Stirling engine, the use of plastic Fresnel lens is preferred over parabolic mirrors due to their lower cost and higher resistance to breaking [38]. Figure 2.4 shows a 1kW Stirling engine developed by Microgen which could be used to convert heat energy from wood pellet boiler into electricity [39, 40]. This system could be used on-farm and wood can be replaced by livestock waste as a fuel for the engine.

Power Source	**Pros**	**Cons**
Generator	1. Cheapest 2. Easy to install and operate	1. Expensive fuel 2. Short life expectancy 3. Require frequent maintenance 4. Polluting (when using diesel)
Wind Turbine	1. Cheaper when compared to photovoltaic [34] 2. No fuel required 3. Clean	1. Very high maintenance costs 2. Effective only in high wind areas 3. Lower performance in low to moderate wind conditions 4. Skilled labor required to install
Photovoltaic	1. Moderate initial cost 2. No fuel required 3. Clean	1. Low maintenance requirements 2. High safety requirements from theft and vandalism 3. Investment required to expand to match the power needs 4. Low performance on cloudy day
Stirling Engine	1. Higher thermal efficiency when compared to photovoltaic 2. Can operate on variety of fuels including solar. 3. No threat from theft or vandalism 4. Require little investment to expand to higher power requirements 5. No risk of explosion when compared to diesel generator 6. Clean	1. High initial cost 2. Require frequent maintenance

Table 2.1: Comparison of potential power sources for use in groundwater pumping.



(a) Stirling engine

(b) Stirling engine as used with pellet boiler

Figure 2.4: A 1kW Microgen Stirling engine and its adaptaion for the OkoFEN-e wood pellet boiler.

Image courtesy: OkoFEN-e

Chapter 3

The Stirling Engine

3.1 The Stirling Cycle Machine

These imperfections have been in a great measure removed by time and especially by the genius of the distinguished Bessemer. If Bessemer iron or steel had been known thirty five or forty years ago there is a scarce doubt that the air engine would have been a great success. It remains for some skilled and ambitious mechanist in a future age to repeat it under more favorable circumstances and with complete success. (Dr. Robert Stirling, 1876)

The Stirling cycle machine was invented in 1816 by a Scottish clergymen Revd Dr. Robert Stirling [41]. It is a unique device in the sense that it's theoretical efficiency is equal to that of a Carnot cycle machine [42]. The main motivations for Robert Stirling to build this machine were to pump water from a quarry and that he wanted to build an engine which operated at lower working pressure than existing Watt's steam engines. However, the understanding of the theoretical basis of Stirling cycle required the geniuses of Sadi Carnot, William Thomson (Lord Kelvin) and McQuorne Rankine. The Stirling cycle is a closed regenerative thermodynamic cycle where the conversion of heat to work (or vice versa) takes place due to cyclic compression and expansion of the working fluid [42–44]. Unlike the Diesel or Otto cycle, the Stirling cycle has a fixed-mass of working fluid constrained in a volume and the flow is controlled by the internal volume changes. Since there is no need to exhaust or vent the working fluid, a prime mover operating on a Stirling cycle does not require any valves and is a clean engine with no pollution.

The machines operating on the Stirling cycle gained widespread popularity in 1820-1830, mainly because they were safe to operate owing to low working pressures and required less skilled labour. However, the invention of the internal combustion engine in mid 18th century, the arrival of the electric motor and a lack of high temperature materials led to a rapid decline in use of Stirling machines. While there is very little doubt about the technical and economic superiority of an internal combustion engine running on gasoline, the requirements of the 21^{st} century dictate the use of machines which run on renewable energy sources and are less polluting [45]. The solution may lie with Stirling cycle machines. The size, energy density and economic constrain may not favor the replacement of internal combustion engines in automobiles with these machines, but they definitely offer a good promise as a replacement for other uses of internal combustion engines like that of pumping water or as mobile power stations [42, 45, 46].

3.2 Why Do We Need a Stirling Machine?

Some reasons why we need a Stirling machine in 21^{st} century is its non-polluting nature, ability to use any heat source (e.g. solar radiation, biogas, natural gas etc), high thermal efficiency (equal to Carnot efficiency), quieter operation, longer life (the Stirling engine has no valves or fuel injection systems) and its good performance at part loads [47].

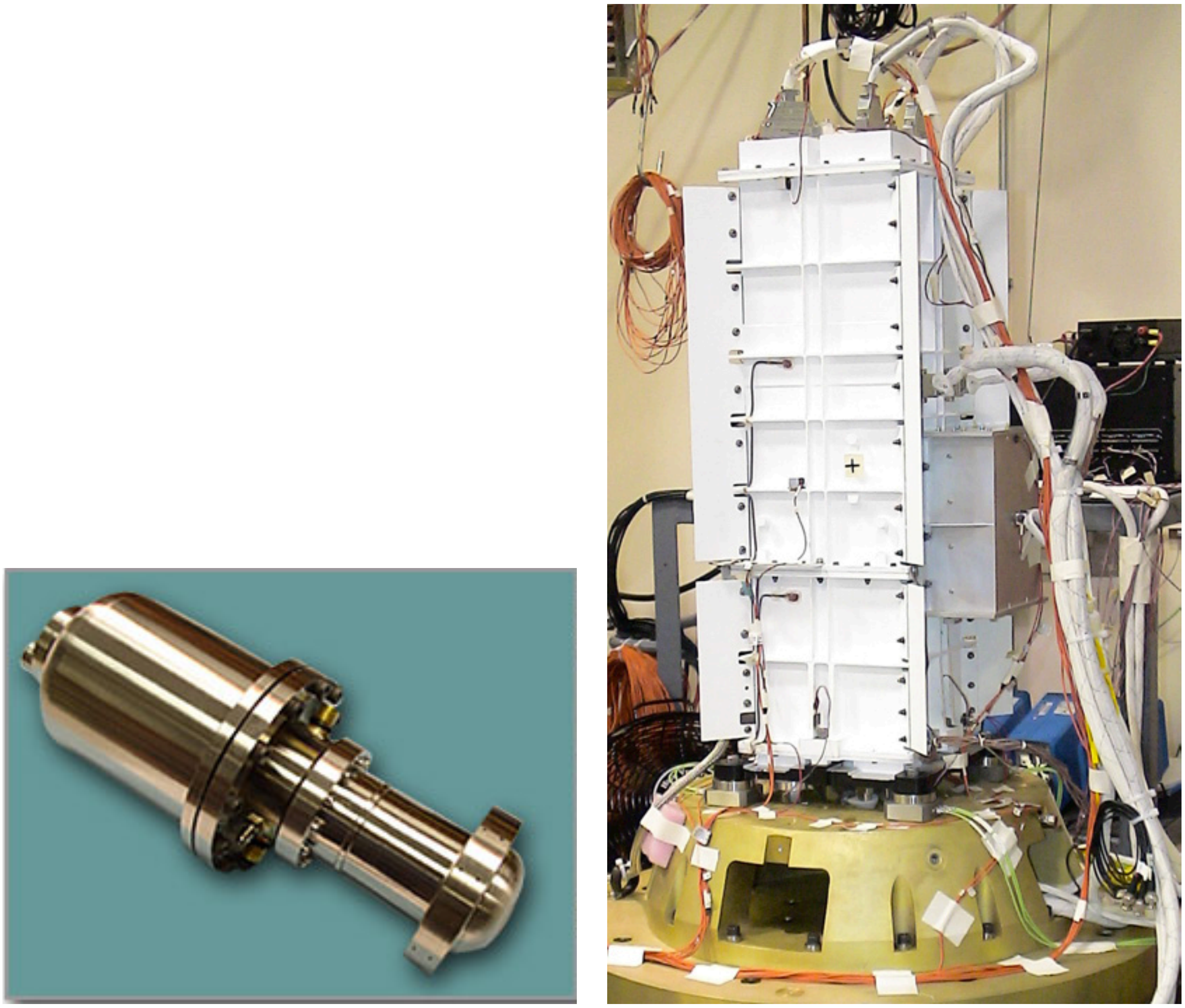
3.3 Stirling Engine Applications in Space Missions

There has been renewed interest in utilizing nuclear powered Stirling engines to generate power for future NASA missions. In the past, NASA missions (e.g. MSL-Curiosity, Cassini, Voyager 1, Voyager 2, Apollo Missions) have been using Radioisotope Thermoelectric Generators (RTGs) to power missions for which solar power is not viable. The other power systems like photovoltaics (e.g. Dawn, Juno) and battery systems (e.g. Hubble Space Telescope) are feasible for shorter missions where the power requirements are lower [48]. The advantage of nuclear power is that they require lesser packing mass, lesser deployed area [48], and can provide almost limitless power for almost any duration [49]. However, the existing RTGs are efficient only for continuous power supply of upto 5kW [50]. Hence, NASA and Department of Energy (DOE) are pursuing a dynamic system which uses nuclear fission to generate power. One such system called Advanced Stirling Radioisotope Generator (ASRG) is currently being developed by the Lockheed Martin Space Systems, under contract from DOE [51, 52]. For a given mass of nuclear fuel (PuO_2), the Stirling cycle has a higher thermal efficiency when compared to the RTGs and offers a four-fold reduction in nuclear fuel [51]. NASA has recently expanded the ASRG program and has given the contract to Sunpower Inc. to build a Advanced Stirling Convertor (ASC) under the guidance of NASA Glenn Research Center (GRC) [51, 53]. ASC uses a free-piston Stirling engine and a linear alternator to generate a specific power from 3 kW/kg to 7 kW/kg [51]. Figure 3.1 shows the ASRG and ASC units.

There have been several other studies on using a dynamical power system, such as Brayton and Stirling cycle for future robotic pre-cursor, resource utilization and manned missions [48, 54].

3.4 Ideal Stirling Cycle

On the principle of the motive power of heat Stirling's Air Engine is constructed. It is very simple. One mass of air alone is necessary to drive it. Here we have a large cylinder with a plunger in it. Suppose it to be at the top. There is a considerable quantity of air below. If we apply the spirit lamp below and heat the air it expands and rushes up along the sides of the plunger, along the tube and forces up the piston in the other small cylinder. There is a wheel placed between the two cylinders. There is a crank attached to each end of the axle of the wheel. When the small piston rises it turns round the wheel which brings the plunger down and this drives out most of the heated air. The air in coming in contact with the cool metal at the top contracts and



(a) ASC model (b) ASRG-EU undergoing launch vibration test

Figure 3.1: The Stirling engine generators currently under development at NASA.
Image courtesy: NASA [51, 53]

draws down the piston which raises the plunger and again the air is heated and so on. In order to condense the air better it is expedient to have a stream of water rushing over the upper part thus carrying away the heat. (Lord Kelvin in 1850 explaining the Stirling's air engine to his natural philosophy class[55])

The above lecture by William Thomson (Lord Kelvin) is probably one of the earliest description of working of a real world Stirling engine. However, the processes occurring inside the engine (e.g. heat transfer from spirit lamp to the air inside the chamber) are complex and, from a theoretical standpoint, hard to explain through compact set of equations or formulas. Hence, for a better understanding of a real world Stirling machine, be it a prime mover or a refrigerator, we need to study them by making suitable assumptions (e.g. infinite rate of heat transfer between spirit lamp and the air inside the chamber). A thermodynamic cycle can be defined as a closed loop cycle made up of multiple processes in a way that at every process one of the properties of working fluid is held constant. The other important assumption made in study of thermodynamic cycle is that of thermodynamic equilibrium or local reversibility i.e. all the processes which the working fluid undergoes are reversible and that there is no friction. In that sense they are ideal. The efficiency of an ideal thermodynamic cycle gives an upper limit on the maximum efficiency which the real world cycle can achieve.

The ideal Stirling cycle [56, 57] comprises of four processes: two isothermal (constant temperature) and two isochoric (constant volume) processes. Let us consider Lord Kelvin's set up for understanding these processes. Figure 3.2 shows the schematic of his set-up. In his set-up there is one large cylinder with a plunger while the other is a small cylinder with a piston. It is the relative motion of piston and plunger which converts heat into net work. As the small piston moves up, the plunger moves down and vice versa. To start the cycle, we will assume that the plunger is at top position and the piston at the bottom position, respectively. It is very crucial to note that the plunger has a high mass and has more clearance for the hot air in large cylinder to go into the small cylinder and vice versa. The motion of plunger is governed by the motion of small piston. A Stirling cycle machine when working as a prime mover moves around the working fluid in such a way as to compress the fluid in the cold part (small cylinder) of the engine and expand it in the hot part (large cylinder) of the machine. Heat is supplied and removed through the walls of the engine [47].

The four processes are as follows:

1. Isochoric compression: Heat transfer from the external source (spirit lamp) to the working fluid (air) inside the large cylinder. Under the assumptions of

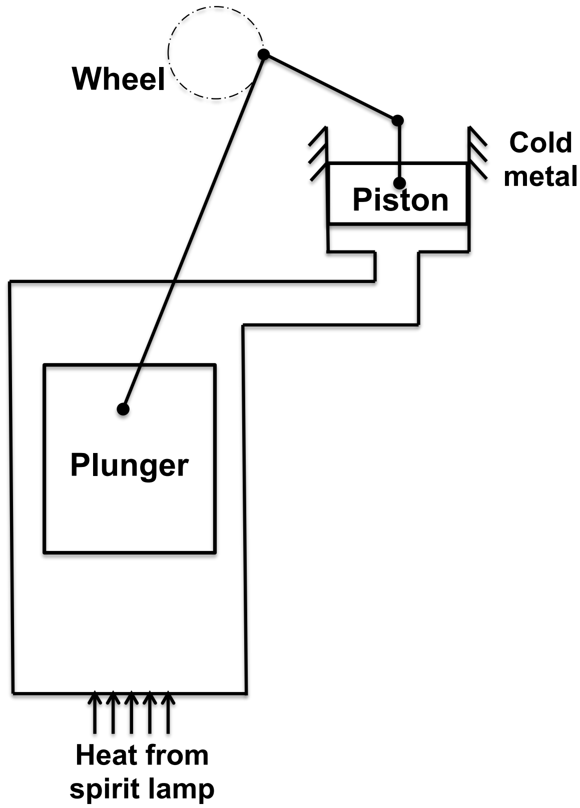


Figure 3.2: Lord Kelvin's account of Stirling's air engine to his natural philosphy class [55]

infinite heat transfer, this process is isochoric, as neither the plunger nor the piston moves. The hot air instantaneously rises along the the plunger sides, through the tube and starts to enter the small cylinder. All of these processes happen instantaneously. It is called compression because heat is being supplied at infinite rate such that there is no movement of either the plunger or the piston and hence the isochoric. The temperature of working fluid becomes equal to the external source temperature T_h.

2. Isothermal expansion: Heat transfer from the working fluid to move the small piston. This is the work stroke. The heated air enters the cold part i.e the small cylinder and pushes the piston upwards which rotates the wheel. As a result, the plunger in the large cylinder comes down. The process is called 'expansion'

because the heated air expands in the hot part of the engine i.e. the large cylinder, and is called isothermal because the temperature of the working fluid remains at constant at T_h. The reason being the infinite rate of heat transfer assumption and the high clearance between the plunger and the walls allowing a medium for heat to flow.

3. Isochoric expansion: Heat transfer from the working fluid to the external sink (cool metal). Once again, under the assumptions of infinite heat transfer, this process is isochoric. When the piston is at the top position, the external sink rapidly cools the working fluid in small cylinder. The plunger at this moment is still at the bottom most position. The temperature of working fluid becomes equal to the external sink temperature T_c.

4. Isothermal compression: Transfer of working fluid from the small cylinder into the large cylinder. The momentum of the wheel brings down the piston thereby flushing the cold air into the large cylinder. The plunger moves up, the air gets again heated and the cycle repeats. It is called compression because the piston compresses the gas in the cold part i.e. the small cylinder, and isothermal because of infinite rate of cooling by the sink. The air remains at the minimum temperature T_c.

Since the heat acceptance and rejection processes happen at constant temperature T_h and T_c respectively, the thermal efficiency of the ideal Stirling cycle is same as that of ideal Carnot efficiency i.e.

$$\eta = 1 - \frac{T_c}{T_h}$$

.

So it is in this sense that the idea Stirling cycle is as efficient as a Carnot cycle and even has a larger area under the PV curve implying larger work done. However, the Stirling cycle has more net work output when compared with the Carnot cycle. This is due to two isochoric processes instead of isentropic in Stirling cycle. Figure 3.3

shows the comparison of the Carnot and Stirling cycle on the PV diagram.

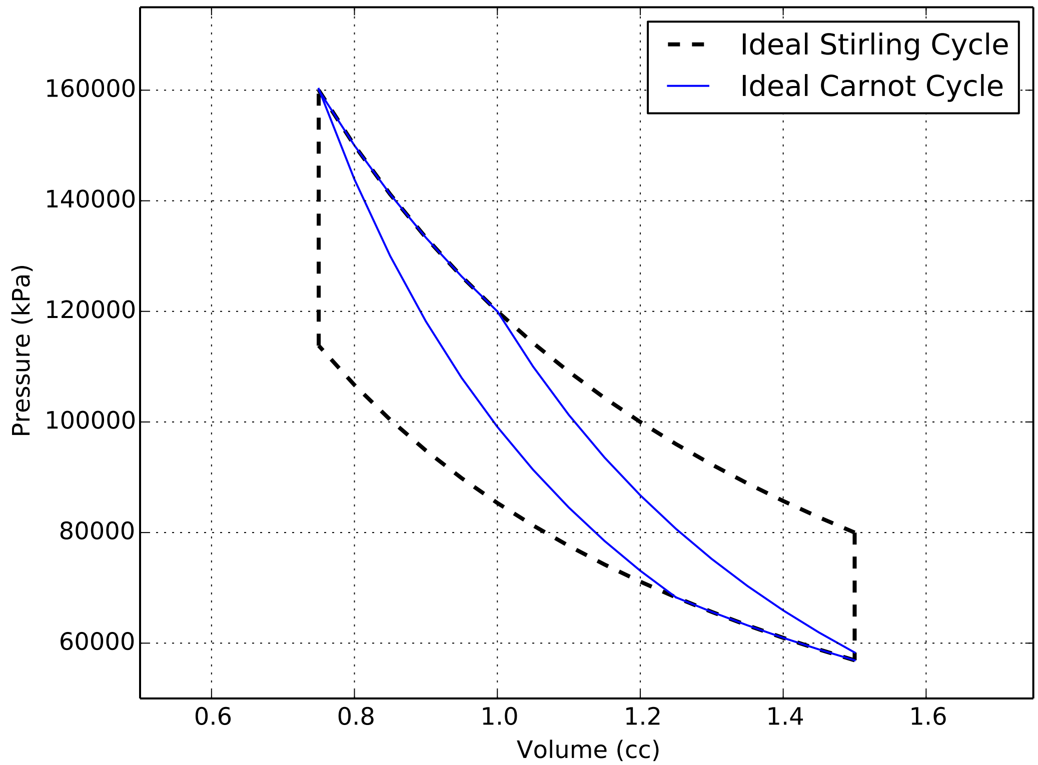


Figure 3.3: Superimposed Stirling and Carnot cycles. Same values of maximum (and minimum) pressure and volume are used.

Careful analysis of the switch between the isothermal compression and isochoric compression reveals a state of working fluid which is not achievable in the real world. Consider as the cold air moves from small cylinder into the larger cylinder through the tube, it is required to remain at the minimum temperature T_c till the piston has reached the bottom most point and then instantaneously gets heated up by the external source via isochoric compression. In the real world, this will be hard to achieve and will drastically reduce the efficiency of the Stirling cycle. To overcome this, Robert Stirling had invented a device called the economizer and placed it at the center of the tube connecting the two cylinders. An economizer (also called as regenerator) can be thought of as a heat reservoir, storing heat when hot fluid passes through it and releasing heat to the cold fluid in next cycle. This, in our above example, would preheat the cold air when it is entering the big cylinder during isothermal compression. This led to a dramatic improvement in the efficiency of the real world Stirling engine.

3.5 Practical Stirling Cycle

The real world efficiency of a Stirling cycle machine is much lower than that estimated by the ideal thermodynamic analysis [42, 43]. This is due to the following reasons:

1. Dead volume within the engine: Since a Stirling engine works on a closed cycle, the mass of the working fluid directly contributes to the net work output. In the ideal cycle, it is assumed that all of the working fluid gets heated and contributes to the power stroke. This is however not correct as some of the working fluid is trapped within the dead volume in both the cylinders. The dead volume is the sum of all the volumes within the working chamber which is not swept by the pistons. Major contributors to the dead volume are the clearances, internal volume of associated ducts and ports and the volume occupied by the economizer [42]. Recent studies conclude that in a real Stirling engine, the dead volume can contribute upto 50% of the total volume and account for a major reduction in the power output [58–60]. The power reduction is proportional to the ratio of dead volume to maximum gas volume [47]. While the dead volume cannot be completely eliminated in any real engine, its effect on the Stirling engine performance is adverse [61] because of the volume of gases that get trapped in the economizer. Isothermal analysis done by considering linear and sinusoidal variations of dead volumes within the economizer conclude that the dead volume strongly amplifies the imperfect regeneration thereby effecting the engine efficiency [62].

2. Departure from isothermal assumption: One of the major departures from ideality is the assumption of infinite rate of heat transfer to and from the working

fluid by external source and sink, respectively. Several authors have concluded that for reasonable speed of the engine (approx. 1000 rpm), these processes are more adiabatic (no heat transfer) rather than isothermal (infinite heat transfer) [42, 44]. To make the actual processes closer to isothermal, a heater and a cooler are placed near the large cylinder and the small cylinder, respectively [42]. The objective of these is to assist in rapid heating and cooling during the isothermal expansion and compression phase. But this contributes to the dead volume which in turns effects the engine performance [42, 44, 61].

3. Flow losses and heat transfer through the economizer: The main function of the economizer (or regenerators) in a Stirling machine is to provide a thermal reservoir to the working fluid. A perfect economizer assumes no viscous losses and infinite heat transfer to the working fluid, which in reality, is impossible to achieve. A well-designed economizer provides sufficient thermal contact to the fluid and minimizes the viscous losses [63]. The sinusoidal piston motion inside the cylinder [61] causes the working fluid to be cyclically distributed in time-variant manner inside the total volume, hence the total mass of the working fluid contributing towards the power stroke is reduced when compared with the ideal cycle. The periodic distribution of the fluid causes the Reynolds number for the flow through the economizer to oscillate. The Nusselt number, heat transfer coefficient and the friction factor are all reported to be higher for oscillating flow when compared to unidirectional flow through the economizer [64, 65]. While high heat transfer coefficient is favorable, the high friction factor contributes to the viscous flow losses.

4. Discontinuous motion of the pistons: In an ideal Stirling cycle, the piston motions are discontinuous. This is because we assume that the heat transfer to and from the working fluid occur at constant volume (via isochoric compression and expansion). However, in a practical Stirling engine, the piston never stops at the end points due to inertia in the flywheel. This leads to a smooth continuous PV diagram diagram within a lesser area under the curve available to

overcome the mechanical and friction losses and provide positive power to the engine. The smooth motion is also a consequence of the dead volume within the engine. Figure 3.4 shows the comparison between ideal and practical cycle piston motion on the PV diagram. One of the critical parameters for the efficient performance of practical Stirling engine is the instantaneous phase angle between the two pistons [61].

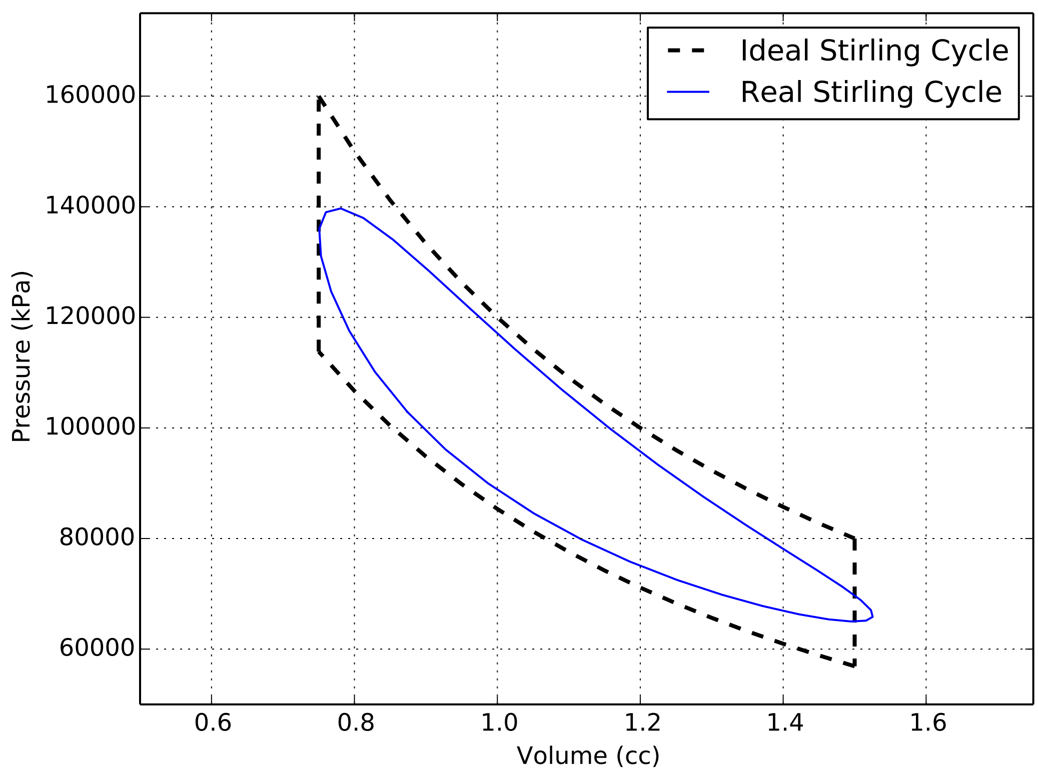


Figure 3.4: Comparision of ideal and practical Stirling cycle for same value of mean pressure, maximum (and minimum) pressure and volume

The dead volume, the continuous motion of the pistons, the limited heat transfer to and from the working fluids, and viscous losses through the economizer contribute to the reduction of the theoretical Stirling efficiency by about 30-35% [42]. The other reason which limited the use of the Stirling engine was the high thermal stresses which the engine material has to go through. Historically, this constituted a considerable design challenge, as well as placed an upper limit on the maximum temperature at which the engine can operate. While this was also the challenge for other engines in that era (e.g. gas turbine engines), the high energy density of liquid fuels when compared to any external combustion sources (e.g. burning of wood, solar radiation) favored internal combustion and turbine engines over Stirling engines.

However, recent advances in material sciences [66–68] and the need for cleaner engines have increased the interest in Stirling engines [69–71]. Recent Stirling engines have been built for brake power varying from few watts to a megawatt, with the power density comparable to diesel engines.

3.6 Types of Stirling Engines

A wide variety of Stirling engines have been manufactured mostly by Siemens, Phillips and General Motors [42, 72, 73]. Any Stirling engine will have the following components:

1. External heat source: Since the combustion takes place outside the engine, a provision must be made for an external heat source and a mechanism for heat transfer from the heat source to the working fluid. Usually, a solid metal with high thermal conductivity is used to transfer the heat from the source to the working fluid [47]. The transfer of heat is primarily by thermal conduction from the metal to the working fluid hence the fluid must also have high thermal conductivity. Hydrogen, helium and air are some prime candidates for the choice of working fluids.

2. Expansion and compression region: As mentioned earlier, the Stirling engine expands the heated gases and compresses the cold part of the gas by using the momentum of the flywheel. Hence, a Stirling engine should have an expansion region (usually large) which allows the heated gas to expand and pass into the compression region (usually small) and move the piston [42, 47]. The two regions can be part of single chamber, as in case of the Beta type of Stirling

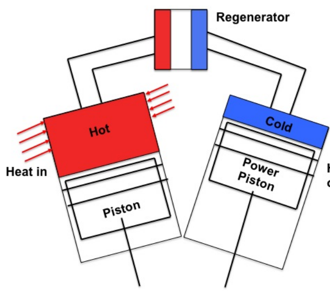
engine. A provision needs to be made for the cyclic motion of working fluid between these two regions. This is accomplished by having a displacer or a plunger with high clearances in the expansion region for working fluid to flow to and from the expansion and compression regions, respectively.

3. Economizer (or Regenerator): An economizer needs to be placed somewhere in the path of the working fluid for it to exchange heat. The role of the economizer is to store the heat when hot fluid is expanding into the compression chamber and transfer it back to the fluid (to preheat it) when it is returning back after compression into the expansion chamber. The design and effective placement of economizer is crucial to the performance of Stirling engine as the former contributes to the dead volume which adversely effects the power output from the engine.

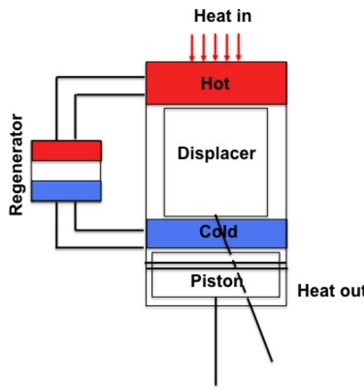
4. External heat sink: Like all engines, the Stirling engines also need to reject the heat to an external sink. Usually running water is used as a heat sink.

Stirling engines have been classified based on the geometric configuration of the expansion and combustion region. In an Alpha type of Stirling machine, the expansion and the compression region are in two different chambers connected by a tube in series which contains the regenerator. There are two pistons in each chamber which move the fluid from one chamber to another. The piston in the expansion chamber has larger clearance to allow heated gas to expand. This configuration is simple to build and is most common. The Beta and the Gamma type of Stirling machines use a displacer and a piston (also called the power piston) to move the fluid around. The job of the piston is to compress the working fluid while that of a displacer is to move the fluid. In Beta configuration, the displacer and power piston are inline in one chamber. In Gamma configuration, the displacer and power piston are offset and are contained in two different chambers. The chambers can either be designed vertically or horizontally. In this configuration, the power piston does both the jobs of compression and expansion. Figure 3.5 shows the three engine configurations. The other class of Stirling engine are called double-acting Stirling engines and were invented by Sir

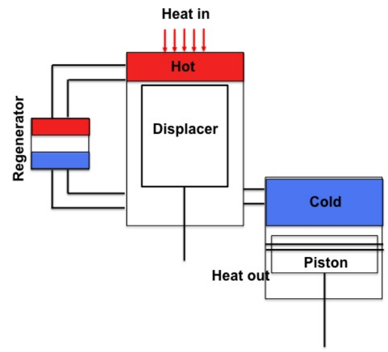
William Siemens [42]. These have four alpha Stirling engines connected in series. The vertical Gamma engine configuration with double-acting piston has theoretically the highest possible mechanical efficiency (80.9%) because of the symmetric gas pressure patterns acting on each side of the piston [43, 74].



(a) Alpha



(b) Beta



(c) Gamma

Figure 3.5: Schematic of the three types of Stirling engine.

3.7 Review of Stirling Engine Optimization

The recent interest in Stirling engines have spurred numerous studies related to the factors which contribute to the Stirling cycle performance and power output. The study done by Kaushik et al. concluded that the heat conductance between engine and the reservoir and imperfect regeneration coefficient are the important parameters which effect engine performance [75, 76]. Timoumi et al. developed a numerical model by taking into account the various losses inside the engine and concluded that the reduction in regenerator matrix porosity and conductivity led to increased performance of the Stirling engine [77]. Asnaghi et al. performed a thermodynamic analysis for the SOLO 161 Solar Stirling engine and concluded that the work output is maximum when the phase angle between the two pistons is equal to 90 degrees while the efficiency is maximum when the angle is around 110 degrees [78]. Costea at al. developed mathematical model describing the irreversible process in solar Stirling engine. They conclude that the pressure loss due to fluid friction inside the engine, and the mechanical friction between moving parts decrease the efficiency in the engine by 50% when compared with ideal Stirling cycle efficiency [79].

Based on above studies the following conclusions can be made about current state of art in Stirling cycle performance:

1. The regenerator volume, matrix porosity and the material's thermal conductivity play an important role in Stirling engine performance.

2. The dead volume contributes to about 50% loss in engine efficiency.

3. Flow losses associated with regenerator need to be minimized.

Chapter 4

The Stirling Engine: A Solution to Energy-Water Nexus

4.1 Overview

The ability of the Stirling engine to operate on green fuels and contribute zero in operation to the green house gas emissions makes it an ideal candidate to solve the energy-water nexus described earlier in the thesis. With recent interest by NASA, DOE and other private companies to adapt the Stirling cycle for cleaner power production provides a justification to use it as a replacement for current diesel and electric pumps being used to pump groundwater. With this in mind, a conceptual design of solar-powered Stirling engine using a Fresnel lens is developed to generate power to operate water pumps in developing countries.

4.2 Design Objectives

The goal is to develop a 4kW Stirling engine which would be able to lift water from 150 feet at 75 gallons per minute. The numbers are chosen based on the average farm size holding and power of existing pumps used by farmers in developing countries. The design should be flexible to adapt to use other fuels (e.g. biomass, rice pellets) which are easily available on the farm. The other consideration is to use commercially available materials and off the shelf parts to make it cost effective and robust.

4.3 Design Challenges

4.3.1 Stirling engine

The main challenge in the Stirling engine design is the engine dead volume and the pressure seals for the pistons. The pressure seals are the weakest link in the design of the Stirling engine as the thermal efficiency is proportional to both the mean engine pressure and also the mass of the working fluid. The thermal efficiency of the Stirling engine also depends on the temperature difference between hot and cold part, hence there should be an efficient heat transfer from the heat source to the hot part and from the cold part to the sink. The other constraint is the choice of working material. Unlike the reciprocating engine (e.g. gasoline engine or diesel engine), the hot end of the Stirling engine is continuously exposed to the maximum temperature and hence thermal stresses. This puts a metallurgical constraint on the choice material for the Stirling engine. On the other hand, the reciprocating engines see the maximum temperature only momentarily and thus have wider range of possibilities for the choice of material.

The other challenge is the efficient transfer of heat from the heat source, which in our case is the solar radiation, to the working fluid. Using solid metal like copper rod to heat the working fluid is not efficient as it creates local hotspots in the expansion region. The outside of the engine needs to be insulated very well to prevent thermal heat losses to the surroundings. At the same time, the engine should be able to effectively reject the heat to the sink to cool down the working fluid.

4.3.2 Solar concentrator

The most common type of solar concentrators are the Compound Parabolic Concentrator (CPC) which reflect the sun rays to a point (called the receiver). The heat from the receiver is then removed by using a heat exchanger and is used to heat the working fluid (e.g. to create steam as in solar thermal power plants). CPC are made up of highly reflecting mirrors which operate on principle of total internal reflection.

The other class of concentrators make use of Fresnel lens [80], which are cost effective and have a higher tolerance to the incoming solar radiation angle. However, almost all the concentrators need solar tracking as their performance drops drastically for diffused radiation. The dual axis tracking mechanism increases the efficiency but adds a significant cost to the solar thermal energy system.

From the energy balance perspective, the solar concentrator will absorb incoming radiation till there is equilibrium with the lost thermal energy to the surroundings. Similarly, the receiver's temperature (which in our design will transfer heat to the working fluid inside the engine) will continue to rise till a steady state is reached between the absorbed solar energy, the convective heat transfer from the receiver to the working fluid, and the radiative and conductive heat losses to the surroundings. Hence the location, temperature and humidity of surroundings, and seasonality become critical in successful concentration and transfer of energy to the working fluid.

4.4 The Conceptual Design

Taking into account the design requirements and challenges, a solar powered Beta-type of Stirling engine with a Fresnel lens concentrator is recommended as a solution for sustainable water pumping. Figure 4.1 shows the schematic of the proposed system. It consist of a Fresnel lens with a secondary optical element, a heat energy reservoir, a Beta-type Stirling generator and the waste heat utilization system which also acts as sink for the engine. Each of the components are discussed in detail below.

4.4.1 Stirling engine selection

To decide on the type of Stirling engine, Schmidt analysis [81] is done to estimate the work done by the three types of Stirling engine for the given hot and cold temperatures. The Schmidt analysis preserves all the assumptions of the ideal Stirling cycle, except that the volume of compression and expansion chamber vary sinusoidally during transfer of fluid [42, 82]. Even though this assumption is not perfect, it is more realistic when compared to the ideal Stirling cycle [42]. A python script is written

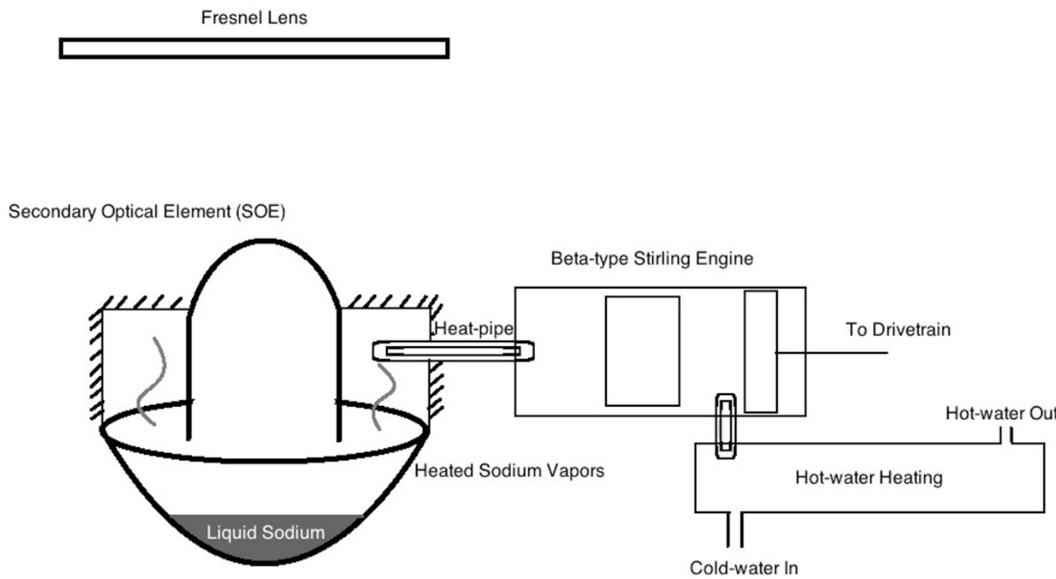


Figure 4.1: Schematic of the overall design of the solar-powered Stirling system. Not shown is the drivetrain and the support for various components.

to solve the equations and the results are plotted using python graphics package matplotlib [83]. Figure 4.2 shows the plot of the three types of engine on the same plot. The area under PV diagram is corresponds to the net work done by the engine. If the design needs to be optimized from a thermal efficiency perspective, then the Alpha-type of Stirling engine will be an obvious choice. However, it is important to understand the assumptions behind Stirling cycle, especially that of perfect regeneration before deciding on the engine type.

As per Schmidt analysis, the Gamma-type of stirling engine has smallest area under PV diagram and hence it is ruled out from consideration. The Beta-type of Stirling engine has a higher maximum pressure, but a slightly lesser area under PV diagram when compared to the Alpha-type. From the perspective of sealing, pressure seals are required on the pistons and are the Achilles heel of the Stirling engine [44]. Displacer sealing is smaller when compared to the piston sealing and has less stringent requirements [42, 44, 72, 73]. Hence, it is better to have a piston and displacer arrangement (as in Beta-type) than the two pistons (as in Alpha-type) requiring two seals. The issue of regenerative heat transfer benefits Alpha-type engine

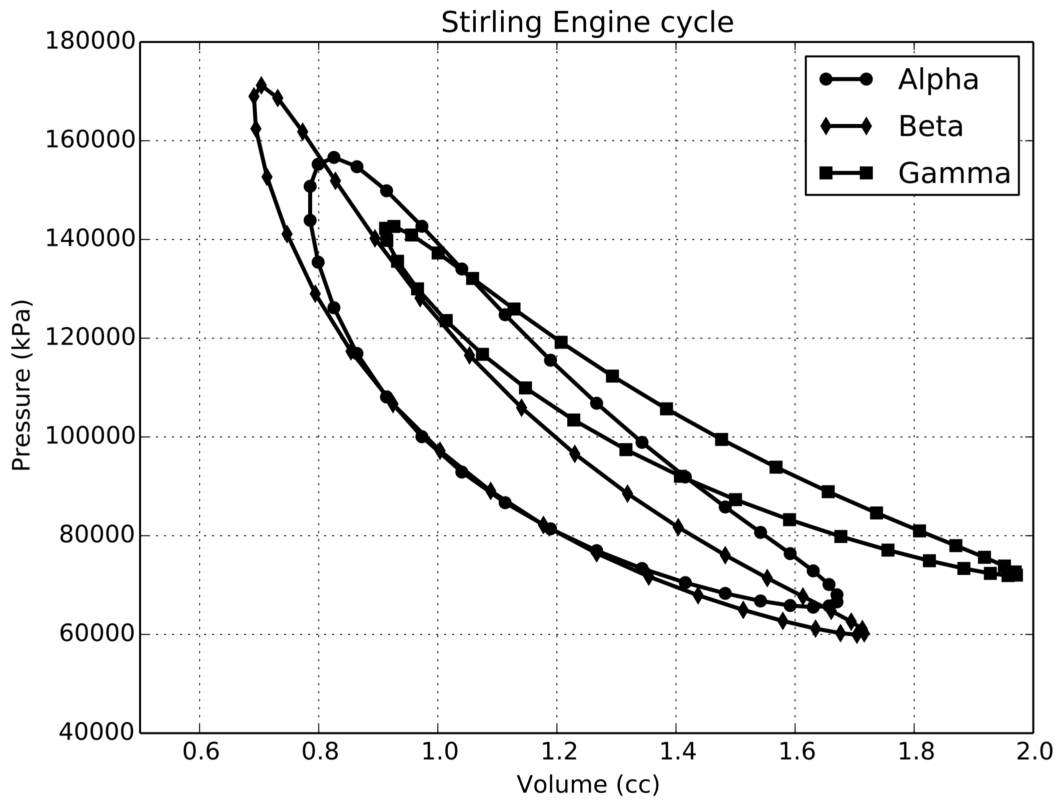


Figure 4.2: The PV diagram for the three types of Strirling engine based on Schmidt analysis.

as it is relatively easy to isolate the hot and cold engine parts because they are in two separate cylinders. Basing the decision based on pressure seals and easy maintenance, the Beta-type of stirling engine is selected for the design. The issue of heat transfer between expansion and compression chamber in Beta-type is addressed in following studies [68, 77, 84, 85] and it is believed that it could be dealt by carefully designing the regenerator.

4.4.2 Solar concentrator selection

The effectiveness of any solar concentrator is defined in terms of solar concentrator ratio (C). It is the factor by which the incoming solar radiation from the sun is concentrated (i.e. multiplied). The second law of thermodynamics places a limit on the maximum concentration (C_{max}) which a body can achieve based on the half-angle (θ_s) between the source and the receiver [86–88]. Mathematically, this can be expressed as:

$$C_{max} = \frac{1}{sin^2\theta_s}$$

For Sun-Earth system, θ_s is 4.65 mrad and hence $C_{max} \simeq 46,200$. However, the actual concentration achieved by using a solar concentrator like parabolic trough or a Fresnel lens on the receiver is much lower than C_{max}. This is due to optical defects and the fact that the commercially available concentrators [45] are designed for half-angle between $\theta_s = 0.5 \sim 1.0$ degree. Hence the actual concentration achieved is in range $3200 \sim 13000$. This assumes that the light ray is nearly parallel at the concentrator, which requires an expensive tracking mechanism to track the sun [46, 89]. The maximum efficiency η_s and the temperature T_{max} which can be achieved for a given concentration ratio can be estimated by using Carnot principle and Stefan Boltzmann Law [56, 57]. For perfect absorptivity, emissivity and no optical losses, the net solar to work efficiency η_s is given as

$$\eta = \left(1 - \frac{\sigma T_r^4}{IC}\right)\left(1 - \frac{T_o}{T_r}\right)$$

Here, I is the incoming solar insolation on Earth ($\sim$ 1000 W m^{-2}) [90], T_r is the receiver temperature and T_o is the sink (or ambient) temperature to which heat is rejected. Figure 4.3 shows η_s for different concentration ratios. For a given concentration ratio, which is limited by the solar concentrator orientation and optical properties, the temperature at which the efficiency is maximum can be deduced from the figure. For example, for $C = 1000$, the maximum efficiency η_s is about 62% and the optimum operating temperature of the receiver T_r is 1100 K. Note that the maximum temperature which could be achieved by the receiver is much more than 1100 K but the efficiency if operated at this temperature will be very poor.

The solar concentration ratio plays a crucial role in determining the efficiency and the net work output of the system. The Fresnel lenses are inexpensive and easily

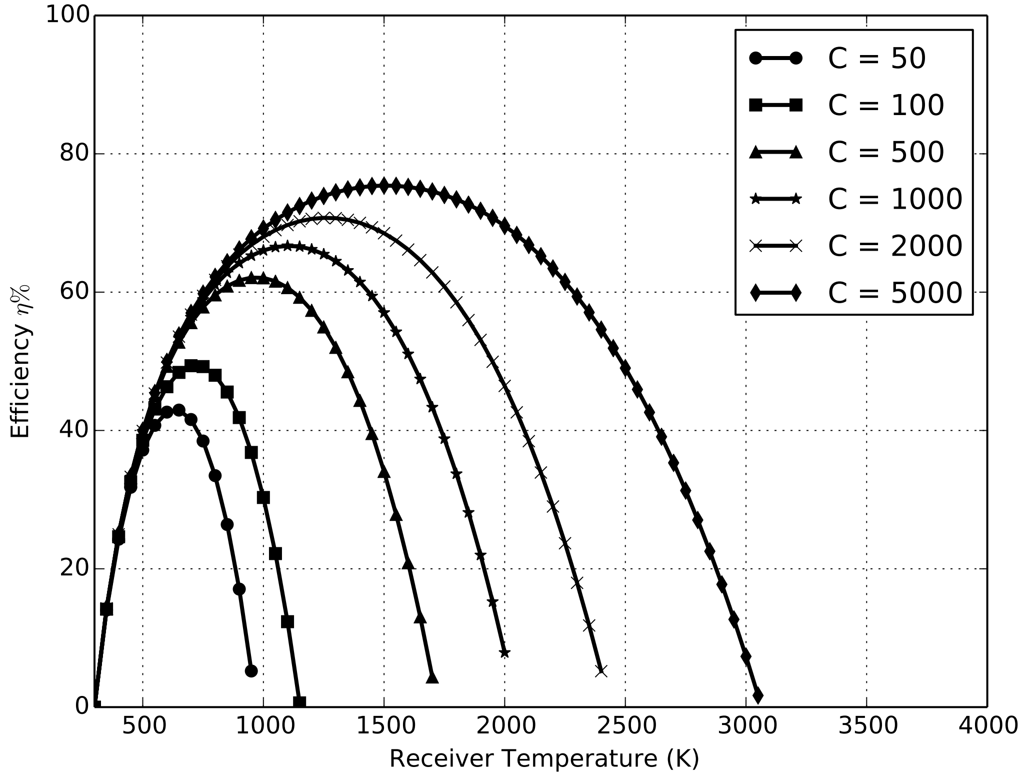


Figure 4.3: The plot of net solar to work efficiency with respect to receiver temperature and for different concentration ratios.

available, however they suffer from chromatic aberration i.e. the failure of lens to focus all the wavelengths in incoming light to a single point. This significantly lowers the concentration ratio achieved by a Fresnel lens (~ 70) [45]. Highly reflective parabolic dishes have an achievable concentration ratio of about 800 but are very expensive and require large area. However, by using a secondary optical element along with Fresnel lens, the incoming radiation falling on the receiver could be made isotropic. An example of the Fresnel-Köhler [91] type of secondary optical element is shown in figure 4.4. For a Fresnel lens with a secondary optical element [45, 92, 93], the maximum practical concentration achieved is about 1700 [45], which gives a maximum operating temperature of the receiver (in our case Stirling engine) of about 1250 K with a maximum efficiency of 65%. The reason for choosing the Fresnel lens over a parabolic dish or trough is its inexpensive and light weight nature [45, 80, 94, 95].

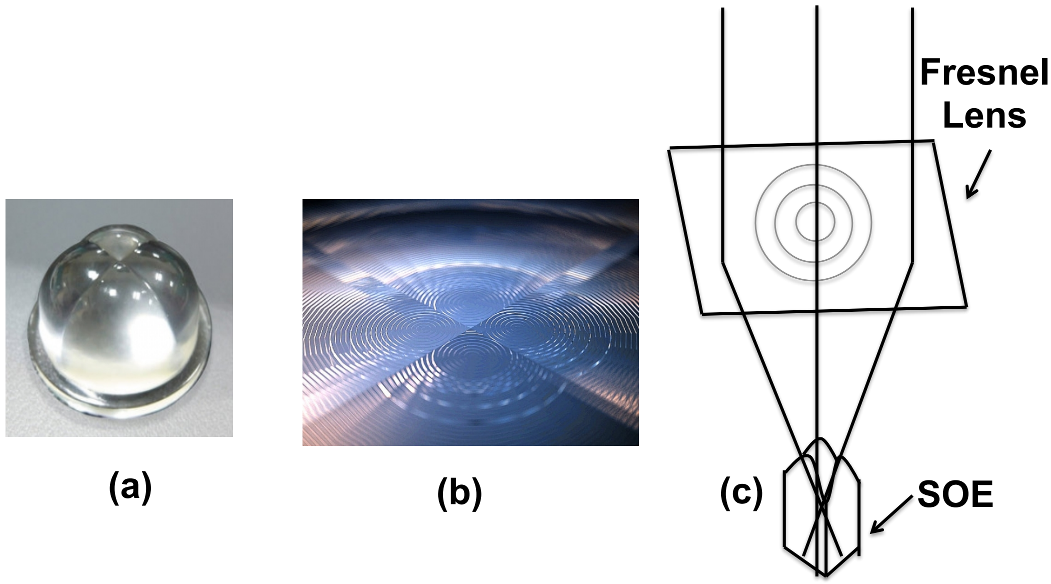


Figure 4.4: (a) The Fresnel-Köhler Secondary Optical Element (SOE) [91], (b) The primary Fresnel lens, and (c) The ray diagram of the light from Fresnel lens and SOE.

4.4.3 Solar receiver and heat transport system

To avoid the fluctuations in the solar insolation, the solar receiver system is designed in a way that it also functions as a thermal storage reservoir. Instead of directly concentrating the light on the heater head of the engine, it is allowed to fall on a spherical dish which has molten sodium inside it. Helium is preferred as the working fluid for the Beta-type Stirling engine as it offers a higher compression ratio for a given volume. This is because of higher degrees of freedom for the Helium molecule as compared to air. Hydrogen would have been an ideal choice, but its combustible nature presents a threat for on-farm applications and would make the system expensive.

Molten alkali metals are used to transfer the heat from the nuclear reactors which are used in space applications [96, 97]. Molten alkali metals have large specific thermal conductivity and specific heat [98]. Their large boiling point (e.g. for liquid sodium is about 900 degree C) allows for higher thermal efficiency [98, 99]. They have been used by various space agencies [99–101] to transfer heat from the nuclear reactor (used to generate power in space) to the heat sink. However, when used in nuclear reactors, the liquid metals become radioactive due to neutron bombardment and require proper shielding [98].

For the present case, molten alkali metals are good choice when compared to water because the latter has high latent heat of vaporization. Also, since our utility does not require any sort of nuclear fission process, hence there is almost no chance of liquid metals becoming radioactive. When the solar insolation is concentrated onto the half-sphere disc (figure 4.1), the liquid sodium vaporizes and condenses on the head of the heat-pipe. The heat-pipe transfers the heat to the engine head in a nearly isothermal manner. The condensed metal vapors are absorbed by a wick and the cycle repeats. Andraka et al. at Sandia National Labs [102] have reported an increase of heat transfer efficiency from 23.2% to 28.1% due to isothermal heating of the engine head as opposed to direct heating.

To transfer the heat from the cold part of the Stirling engine to the heat sink, a water-glycol coolant is circulated using a pump. The power to drive the pump is a parasite loss (5-6%) for the engine power output [103]. The heat in the coolant is then used to heat the water in the tank. The heated water is used by farmers for seed germination, farm facility cleaning and poultry [104].

4.5 Applications of Stirling Engine in Agriculture

4.5.1 Drip irrigation

Drip irrigation is an ancient method to irrigate farms in water scarce regions [21]. It provides small and controlled quantity of water at regular intervals near the roots of the plant [22, 23]. It results in huge savings of water[23, 105, 106] and is one of the fastest growing technology in agriculture [106]. The United Nations is promoting the use of drip irrigation by educating farmers about this technology and supplying manuals in local languages [107]. A typical drip irrigation system consists of a water reservoir, a water pump, pressure regulators, drips (or sprinklers), valves and a control system [21]. The pump in the drip irrigation system could be used to pump water from the ground and store it in a man-made water reservoir (e.g.: storage tank). The water is then distributed via low pressure pump to the drips which supply water near the roots of the plant. Alternatively, if there exists a natural water reservoir (e.g.: nearby lake, river) the water can be pumped directly from the reservoir directly to the drip system. The pumping requirements in former case is set by the pressure head of the water, while in the later case it is set by the area which needs to be irrigated (i.e. the mass flow rate). In both the situations, the pump can be powered by a solar powered Stirling engine. Figure 4.5 shows the schematic of Stirling Drip Irrigation (SDI) system in which the water is pumped from the water reservoir to the drips.

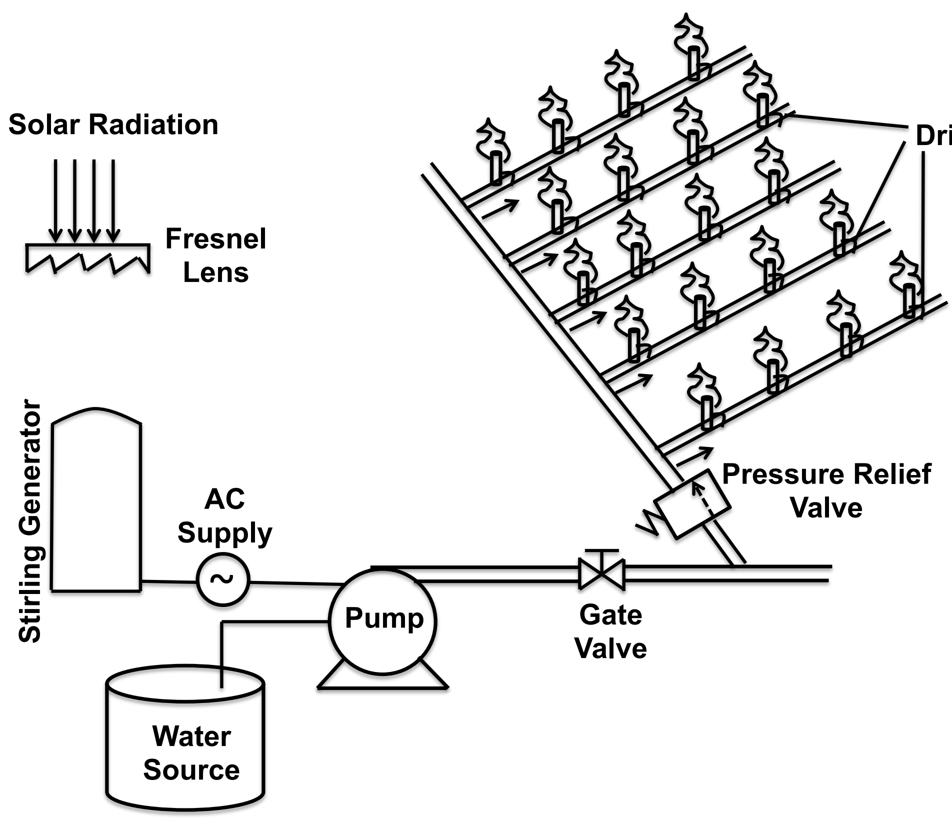


Figure 4.5: Schematic of Stirling Drip Irrigation (SDI) system.

To size the Stirling engine power output, let us consider the case for the irrigation needs of an average farmer in India. Assuming that there exist a 15 feet deep water canal which is used as a reservoir to irrigate a perfectly flat acre of land 1 feet deep in 1 hour. The efficiency of a typical pump which is currently being used by farmers in India is in range 40 - 80% [13]. Assuming the alternator efficiency as 55% and the pump efficiency as 60%, the total Stirling engine power output required is about 1.25 kW.

To understand the feasibility of the SDI system, we can compare it with two other power alternatives: (i) Photovoltaics, and (ii) Liquid-fuel (e.g.: diesel, gasoline, kerosene). Table 4.1 provides the comparison between three power sources with respect to the conversion efficiency and the total cost. The diesel generator has smaller initial investment, has no installation cost but consume diesel to produce power. The small initial investment is the reason why diesel generators are so popular among farmers. Both photovoltaic and Stirling engine have higher initial investment and require skilled labour for installation. Photovoltaic may be a viable alternative to the Stirling engine, however it may not suited for on-farm irrigation purposes due to practical considerations (e.g.: panel breaking due to stone pelting, accumulation of dust on the panels due to farming etc.)

Item	Stirling Engine	Photovoltaic	Liquid-fuel (Diesel)
Conversion efficiency	30-40%	14-18%	15-30%.
Equipment cost	$16500	$3500	$500
Installation cost	N/A	$5000	N/A.
Fuel cost/year	N/A	N/A	$15000.

Table 4.1: Cost analysis of various power sources for use in drip irrigation system.

4.5.2 Food harvesting: micro-cold storage

The other important problem facing the agricultural industry in developing nations is the highly inefficient supply chain. Because of lack of cold chain infrastructure about 30 per cent of all foods produced in India are wasted every year. By building an efficient and effective supply chain, using state of the art techniques, it is possible to serve the population with value added food while simultaneously ensuring remunerative prices to the farmers. The surplus of cereals, fruits, vegetables, milk, fish, meat and poultry can be processed as value added food products and marketed aggressively both locally and internationally. A summary of the problems faced in the cold chain sector in the developing countries are as follows:

1. There is an infrastructure gap of 60% (37 million tons) of required cold storage capacity in India; similar is the case in other developing countries.

2. The cold storages that are currently installed use over 30000 MW of power. The energy costs account for over 30% of the overall running cost of a cold storage facility.

3. Further, the grid supply is highly erratic and conventional cold storage systems use diesel as backup.

4. Given the perishable nature, customer-in-hand quality deteriorates significantly due to lack of good storage facilities.

5. In the absence of a cold storage and related cold chain facilities, the farmers are forced to sell their produce immediately after harvest which results in low price realization to farmers.

To curb the shortage of cold storages in developing countries, the idea of a micro cold-storage is proposed [108]. It makes use of a Stirling engine generator to drive the compressor used in the refrigeration cycle. Since Stirling engines are best suited for stationary operations, the proposed idea is suited for an on-farm small cold-storage ($\sim 2-5$ tonnes capacity). For mobile operations, such as carrying the cold-storage on a truck, use of photovoltaics is suggested. Figure 4.6 shows the sketch of the micro cold-storage system. The Stirling power source is not shown in the figure.

The system consist of three main units: the power supply, the storage compartment and a thermal unit. During the day, the compartment is cooled by using the vapor compression cycle. The thermal unit takes a part of the cooled refrigerant, before it enters the evaporator, to produce ice. This ice is kept in a well insulated

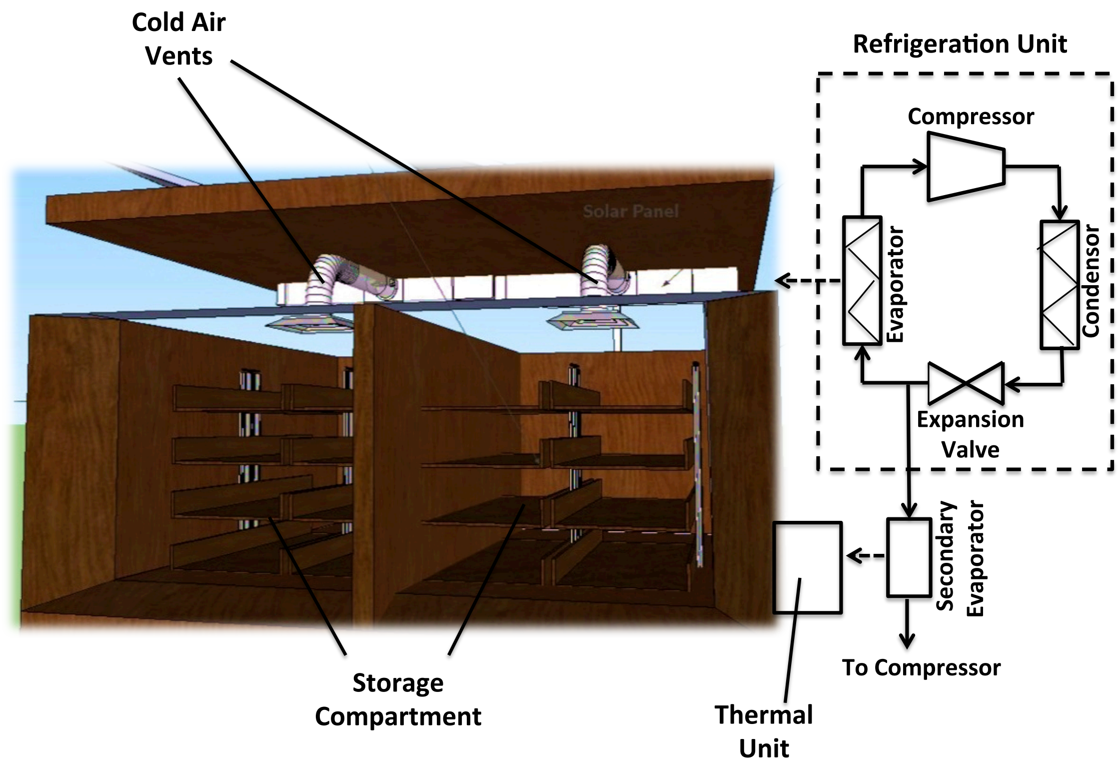


Figure 4.6: Sketch of the micro-cold storage. The refrigeration unit shows the modified vapor compression cycle.

thermal unit and is connected to the storage compartment by heat-pipes. At nights (or when direct cooling is not enough), the refrigeration effect is transferred from thermal unit to the compartment through the heat-pipes. This eliminates the need of the main battery which is usually required in solar powered applications. However, a small battery is used to power a small blower which is required to transfer heat from thermal unit into the main compartment. Since the cold-storage unit is proposed for outside use, it takes the advantage of natural convection thereby lowering the blower fan requirements.

Chapter 5

Conclusion

5.1 Conclusion

The main goal of this thesis is to provide sustainable energy solutions to the two major issues of irrigation and food harvesting in developing countries. The problem of irrigation is two fold: groundwater is depleting at an alarming rate, and the energy required to pump the groundwater comes by burning fossil fuels. The increase in demand for food for our growing population has further elevated the groundwater usage, which in turn requires more energy. The problem of food harvesting is due to highly inefficient cold-supply chain in developing countries. The existing cold-storages make use of electricity, which in turn comes by burning fossil fuels. In India alone, the problem is further worsened by the acute shortage of about 37 million tonnes of cold-storage. This has made agriculture highly unsustainable and one of the most energy intensive industry.

As a solution to the energy part of both the problems, the use of solar energy is suggested. The reason for choosing solar is because of the ample solar insolation which developing nations like India and China receive. To convert solar radiation into electrical energy, the use of Stirling engine is suggested. A conceptual design of solar-powered Stirling generator is resented. For easy maintenance, the Beta-type of Stirling engine is selected over Alpha and Gamma Stirling engines. To make the system cost-effective, a Fresnel lens with a secondary optical element are used as solar concentrator. The secondary element helps to collimate the light and make the solar insolation isotropic thereby increasing the concentration ratio. Molten alkali metals are use as a thermal reservoir for the heat which is then transferred to the working fluid by using heat-pipes. To make the system more efficient, the waste heat from the engine is transferred to heat the water which could be used for on-farm operations. Water-glycol is used as a coolant because of its high heat-transfer coefficient.

For irrigation to consume less water, the use of drip irrigation is suggested. By combining the solar-powered Stirling generator with the drip irrigation, it is envisioned that not only will irrigation consume less water but also do so in a sustainable way. It is the first time the use of such a system has been proposed. While one could use photovoltaics instead of Stirling engine to convert heat into electrical energy, the social barriers like vandalism and theft pose a major security concern to photovoltaics thereby limiting its use for on-farm applications. From cost perspective, a photovoltaic system would probably be cheaper than a Stirling system. However, from an engineering perspective, for the same amount of concentrated solar radiation, Stirling engine is about 10% more efficient than photovoltaics. With renewed interest from NASA and private companies in Stirling technology, it is hoped that the cost to built a Stirling engine would come down.

The problems faced by the agriculture industry today are man-made and could be described as the tragedy of commons. One one hand, engineers can come up with sustainable solutions, but it is up to the government and individuals to make an effort to use them. Government needs to educate farmers about technologies like drip irrigation and regulate the amount of groundwater which could be withdrawn. Pilot projects should be set-up to increase the understanding of new technologies. It is for a reason why it is called a nexus.

5.2 Future Work

While this thesis provides a conceptual design of a solar-powered Stirling generator, there still remain many practical challenges to make it a feasible solution. For example, the orientation of Fresnel lens needs to be continuously adjusted to track the sun, which adds an extra cost to the system. Also, research needs to be done for the high quality materials which are needed to insulate the hot space enclosure so that heat could be effectively transferred to the molten alkali metals from the concentrated light. One possible way to avoid use of hot space enclosure is to keep the focal point of the Fresnel lens inside the engine head to directly heat the working fluid. This would require a study of various optics have high transmission ratios and excellent resistance to high temperatures.

The performance of a Stirling engine depends on the ambient temperature. If water is not available as a coolant, then the efficiency of the engine will drop on a hot day (which is usually the case for on-farm conditions). A detailed theoretical and experimental analysis needs to be performed to identify the potential coolants and to characterize there heat-transfer coefficients. The present design assumed that helium is readily available to be used as working fluid. Since the major producer of helium gas in the world is US, it may pose a challenge to import helium in developing countries like India and China. Hence, it is suggested to look into other possible working fluids which have high thermal conductivity, low viscosity and diffusivity.

There is no available data for the on-farm technologies which use molten alkali metals. Though they are an excellent thermal reservoir, the liquid metal containing space needs to be properly sealed to avoid any contact with air or water. While the guidelines for safe handling of alkali metals exist, it is strongly suggested to carry out thorough experiments on sealing material needed for a safe design.

As the cost of photovoltaic panels is decreasing, it may be viable option to build a hybrid modular system which consists of a Stirling engine and a photovoltaic array as a means to generate electricity. For example, during a sunny day, the system could directly use photovoltaic panels to convert solar energy into electricity. On a less sunny day, the waste from the livestock could be burned to provide thermal energy to the Stirling engine. In another scenario, if there is a need to expand the power output from a existing photovoltaic water pumping system, a Stirling engine could be added with no extra area penalty. However, a detailed engineering analysis is needed to reduce the number of components in such a hybrid design.

Lastly, the selection of Beta-type Stirling engine was made due to a larger area under PV diagram which was based on Schmidt analysis. While Beta-type Stirling engine require less maintenance than Alpha- and Gamma-type Stirling engine, the real world processes which any Stirling engine would follow are far from what is assumed in Schmidt cycle. There do exist other class of Stirling engines like Free-Piston Stirling engine which were not investigated in this study and may perform better than the Beta-type Stirling engine. A theoretical investigation based on Schmidt and Adiabatic analysis for both the engine could provide useful guidelines on selection of engine type.

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