DESIGN & FABRICATION OF SOLAR DISH STIRLING ENGINE

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DEDICATION

Dedicated to our Parents,

Teachers and Friends.

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All praises and tokens of gratitude are to ALLAH who made this possible. It's all His blessings that we were able to complete this project. We would like to express deepest appreciation to the higher authorities, our worthy Vice Chancellor Prof. Dr. Muhammad Aslam Uqaili, Dean of Faculty of Engineering Prof. Dr. Hafeez-ur-Rehman Memon, Chairman of Department of Mechanical Engineering Prof. Dr. Dur Muhammad Pathan and to all the faculty members of the department.

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Sincere Regards,
All Group Members

ABSTRACT

In order to serve the ascending energy needs for power generation globally, keeping in mind the concerns of scarcity and environmental damages that can be provoked by the utilization of conventional resources, a new cleaner and renewable power source needs to be explored, conceptualized, and developed. Solar energy is free, ample and clean energy resource which can be used to generate power without causing harm to humans and the environment. To capture and harness this solar energy efficiently as a feasible power source, a Stirling engine is developed which will use sunlight as its input source using a solar dish concentrator. The heat generated from solar dish concentrator is enough to start up and operate a Stirling engine, and the power could further be extracted, by connecting a dynamo with the flywheel of the Stirling engine thus charging a battery. The fabricated engines maximum power producing capacity is 37 watts and the group was able to produce 15.4 watts using solar energy, which accounts for 41.62% efficiency. The nature of the engine enables for both the scalability to create a solar farm as well as use for producing power in remote areas. It has been demonstrated that there are variations in the Stirling power output for various materials, which helps us choose the best material based on the desired power output and cost.

Key Words: Stirling Engine, Solar Dish, Thermal Analysis, Design, Solar Energy

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Symbol	Description
y	Distance away from the mirror center
D	Diameter
x	Depth
a	Focal length
W_s	Output work in one cycle (J)
V_{SE}	Swept volume of expansion space (m^3)
R	Gas constant (J/kg. K)
T_E	Gas temperature of expansion space (K)
T_C	Gas temperature of compression space (K)
N	Engine speed (rps)
B_N	Beale Number
W_O	Power Output (Watts)
P	Pressure (MPa)
V	Swept Volume (cm^3)
f	Frequency (Hz)
W_N	West Number
CC	Cubic Centimetre
η	Stirling Engine Efficiency
$\eta_{collector}$	Collector Efficiency

CHAPTER#1
INTRODUCTION

1.1 ENERGY CRISIS

Pakistan is one of those developing countries which is facing energy crisis and most of its power generation is based on Oil and Gas resources which are more of conventional sources. These sources are usually fossil fuels. Their use leads to increased greenhouse gas emissions and other environmental damage. So, to address the economic and environmental issues caused by fossil fuels utilization has ignited the idea to shift our power generation methods to renewables which are infinite in nature and are environment friendly. It is our country's best interest to explore heavily renewable energy sources so that we can reap its benefits in environment, economy, politics and human.

1.2 CAUSES OF ENERGY CRISES:

Energy is now the talk of town in Pakistan. Starting from house wives, traders, businessmen, students, ministers all the victims of the shortage of energy. Karachi the biggest city experiencing up to 12 hours load shedding in peak hot weather and during the board exams are on the way. Everybody now became the expert of energy and all the figures are on finger tips, sometimes the shortage is 200 MW sometimes 2500 MW.

1.2.1 AGING OF THE EQUIPMENT:

One very important reason attributed to this energy shortage is the aging of the generating equipment which could not develop the electricity as per the design requirement. This is the responsibility of continuous updating the equipment and keeping the high standard of maintenance. We sincerely think a serious thought should be given for general overhaul and maintenance of existing equipment to keep them in good working order. Due to aging of equipment change over in energy system is required towards a more sustainable system.

1.2.2 WASTAGE OF ENERGY:

So far energy conservation is limited to newspaper ads lip service in seminars. No serious thought is being given to utilize the energy at the optimum level. A new culture need to develop to conserve energy. Sometimes on government level illiteracy is blamed for the failure of the energy conservation program. this is not true. Maximum energy is consumed by elite class which have all the resources of knowledge and communication. But for their own luxury they themselves ignore the problem. Government should seriously embark on energy conservation program.

1.2.3 HIGH COST OF FUEL:

The cost of crude has increased from 40 $ to 140 $/barrel. It means the generation from thermal units are costing exorbitant price. WAPDA and KESC when purchasing electricity on higher cost are not eager to keep on selling the electricity on loss. Therefore, they do not move on general complain of load shedding. One simple solution is to increase the energy cost. Again, the theft of electricity from the consumers adding the misery of common citizen who wants to pay the bills honestly, the problem of the energy losses is being discussed for more than a decade and in spite all efforts no solution has been found.

1.2.4 MISMANAGEMENT AND MONOPOLY IN BUSINESS:

WAPDA and KESC are two generation and dispatch units in Pakistan. Although NEPRA is a government authority to settle the tariff issues but the fact remains that once the question of WAPDA comes the authority has a very little influence. This is suggested that private sector should be allowed to install power plant and settle the electricity to consumers. Once the rates are settled on competitive basis and the service and uninterrupted power supply will be insured then consumers will be benefited.

1.2.5 ROLE OF GOVERNMENT

So far, the government is looking for private sector investment in energy sector and for itself it chooses a role of facilitator and arbitrator. We strongly suggest that a massive investment from government itself in generating units for conventional as well as new technologies is needed. Once the government sector embarks on massive plans then private sector will follow immediately. Technical and economic constraints, political issues, incompetent and discontinuity of energy policies, international embargoes, depletion of fossil fuels like natural gas etc. are other causes for the energy crises.

1.3 MOTIVATION

Solar Energy is the most favorable renewable energy source among all the resources in terms of its availability. Keeping in mind the geographical situation of Pakistan it is most suitable, ample and reasonable source of utilizing energy. Due to its cost-effectiveness, simplicity to be employed and portability, it can directly be used as an input source for various engines (E.g. Stirling Engine).

1.4 JUSTIFICATION

As the whole world is in the transition phase of shifting its power generation resources from conventional sources to renewables for the sake of protecting and preserving the environment which is at stake if this shifting is not carried out and may result in the loss of life on Earth. Because, of the damages caused by the greenhouse gases emitted due to utilization of fossil fuels and the rate of them being utilized is much of a concern to our economic and environmental stability. Our project not only aims at utilizing renewable source of energy but also addresses the simplicity in the construction of the project itself if compared to other method of harnessing the same energy source.

1.4.1 ENERGY MIX OF PAKISTAN:

- Total installed capacity of electricity :22477MW
- Total production of electricity: 11362 MW
- Total Demand of electricity: 16814 MW
- Shortfall :5000 – 6000 MW (approx.)
- Thermal Installed Capacity (Fossil Fuels): 15000MW (approx.): 62% share. (Oil 35.1% & Gas 27%)
- Hydropower: 6595MW (33% share in summers) and 2300 MW in winters

*(In 1995 the energy mix of hydro-thermal was 50-50%)

- Nuclear: 462 MW (3.9% share)
- Coal: 0.16 MW
- Renewables: 42 MW (Solar/Wind)
- Annual Increase in demand 8 – 10%

*These figures are not exact and may vary depending upon season and energy demand, policies.

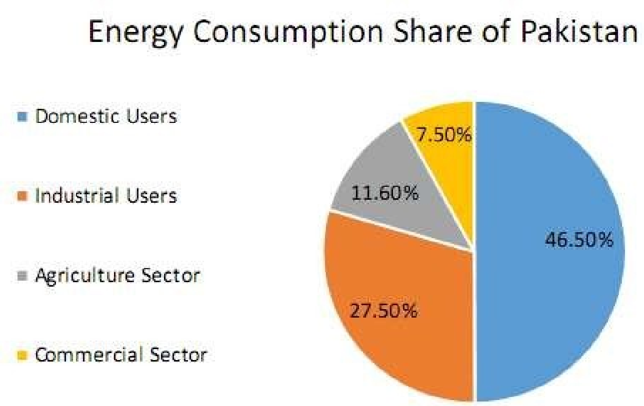


Figure 1.1 Energy Consumption Share of Pakistan

The energy consumption share pie chart shows that 46.5% of the users are domestic putting a significant amount of load on the national grid so it is important to use decentralized energy for domestic use so that the load on the national grid can be reduced and more share can be given to industrial sector contributing in national development.

1.5 PROBLEM DESCRIPTION

In this world of industrialized modernization, the most critical issue is to meet the Energy requirements that have been advancing day by day to a certain peak that it has become much of an impossible task to match certain energy requirements keeping all the social, economic and environmental subject of interests in mind. Exploring non-renewable energy resources is the only feasible alternative to eliminate the power scarcity.

On the other hand, some developing countries like Pakistan are not even able to meet the basic energy demands of the country. This deficit of power generation drives the need to ponder on what other workable options can be opted to overcome the demand. Globalization of renewables has become the prime goal and utter need of the world at present.

1.6 SCOPE & OBJECTIVES

Soon, power plants need to accommodate issues such as the depletion of conventional fuels, the increase in cost of fossil fuels, the use of alternative fuels, the demand for a prime mover that produces less air pollution and less noise, and the amount of waste heat recovery. The Stirling engine addresses these problems as it has multi-fuel capability, high efficiency, low fuel consumption, clean combustion, low noise levels, and low temperature operation. The current research aims to construct a solar powered Stirling engine, test for the most efficient design by using the recorded measurements to calculate the power output to determine to optimal Stirling engine configuration.

The idea is to collect solar energy through reflecting parabolic dish. This energy will be utilized to run a Stirling engine (Gamma Type) which will produce electric power through coupling generator. Solar tracking system will be optional keeping the time constrain in mind.

CHAPTER#2

LITERATURE REVIEW

2.1 ENERGY

Energy is the capacity to do work. Energy is less tangible than matter. Energy can be changed from one form to another. And all these changes i.e. Physical, Chemical or biological take place when this energy is converted from one to another form, for example when heat energy of sun is converted into mechanical energy, during these changes total amount of available energy remain unchanged, as per law of conservation of energy.

2.2 DIFFERENT TYPES OF ENERGY

We have different types of energies i.e.

1. Kinetic Energy
2. Heat energy
3. Electrical energy

2.2.1 KINETIC ENERGY

The energy by which any object moves or to do some work called kinetic energy

2.2.2 HEAT ENERGY

Heat energy is also a kind of energy. Heat travel fast from one place to other and it is always moves from hot place to cooler place. Heat transfers its energy, in three different ways, first is entering a gas or liquid it expands it and become less dense then this makes it rise. Cold gas takes its place to cover that area.

2.2.3 ELECTRIC ENERGY

Now a day without Electrical energy it is almost difficult to live. This energy is used to provide light, to drive motor, etc. Hence it is used in every part of life. And this energy comes from electric current. Now our modern lives depend on continuous supply of electricity. It is very useful, as it can transfer over long distances, and at factories it converted to other form of energy for different purposes.

2.3 ENERGY IN PAKISTAN

Pakistan is a very rich country in terms of energy. Its population is nearly 200 million. The people of Pakistan occupy a land whose geography varies from the lofty mountains in the north to the famous deserts of Thar and includes the fertile plains of the Indus River over 700km coast of south.

In order to fulfill the requirement of energy, Pakistan obtains its energy from different sources requirements from a variety of traditional and commercial sources. The total primary energy consumption in Pakistan is currently estimated at around 60 million tons of oil equivalent (MTOE). Of this, commercial energy resources meet two-thirds with about one-third being based on non-commercial energy resources like charcoal firewood. The primary commercial consumption of 41.7 MTOE is largely based on the use of hydrocarbons. The primary commercial energy supplies are given in Table:

Primary Energy Supplies by Source (2008-09)

Source of Commercial Energy	Primary Energy supplies (%)
Gas	38.61
Oil	42.8
Coal	5.2
Hydro	13.0
Nuclear and other	0.2

Table 2.1 Energy Supplies

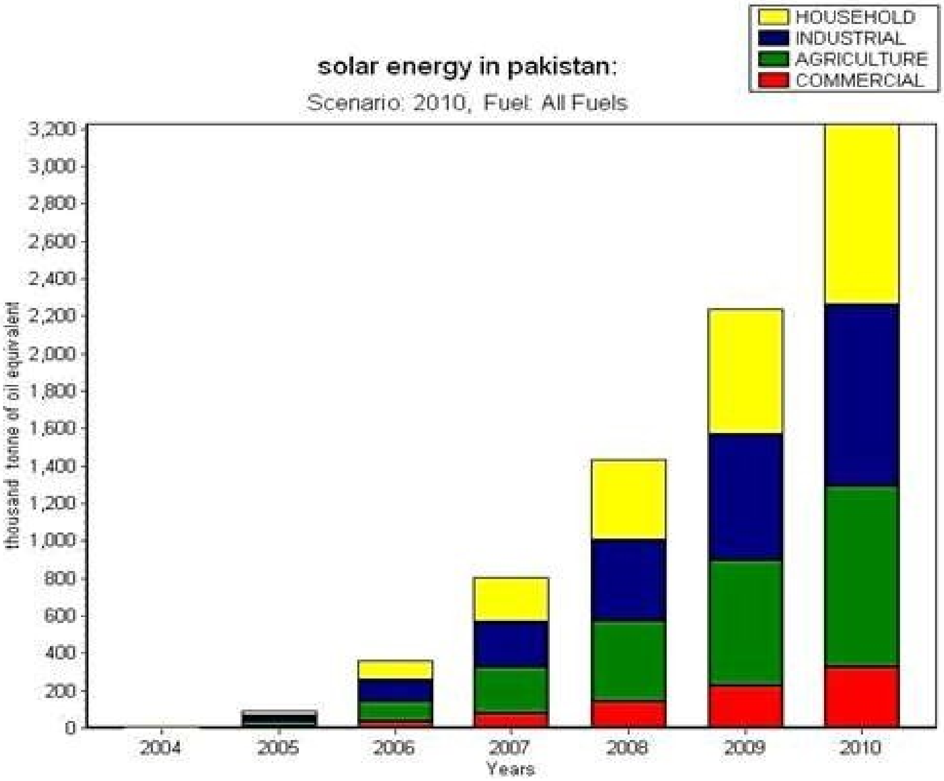


Figure 2.1 Solar Energy in Pakistan

2.4 SOLAR THERMAL APPLICATIONS

There are many applications in which solar energy can be used directly. Such technologies are very simple and of relatively low cost so these can easily be adopted. These thermal applications include heating of comparatively simple, relatively low cost and can easily be adopted. The applications include cooking, cooling of buildings generation of high temperature steam, heating water for domestic and industrial applications.

2.4.1 SOLAR WATER HEATERS

Solar water heating technology is more popular and used in many countries of the world. In this technology sun rays are used to heat the water and to convert to steam. This technology in Pakistan is not used commonly yet because of its cost.

2.4.2 SOLAR COOKER

Solar cookers are used for cooking in many countries now. And different organizations are still working for development of low cost and design for both type of solar cooker (both box and concentrator type).

2.4.3 SOLAR DRYERS

Solar dryers are the devices which are used to drying the agriculture products. These are used under controlled atmosphere. So, by using this technology we get good quality products at much less cost. Now a day's these solar dryers are used to dry some kinds of fruits transport these fruits and then sell letter in market.

2.4.4 SOLAR POWER GENERATION

There are different methods to use sunlight to produce electricity. It has been present in many traditional building methods for centuries, but has become of increasing interest in developed countries as the environmental costs and limited supply of other power sources such as fossil fuels are realized. It is already in widespread use where other supplies of power are absent such as in remote locations and in space. As the Earth orbits the Sun, it receives approximately 1,400 W / m^2 of energy, as measured upon a surface kept normal (at a right angle) to the Sun.

2.5 TECHNOLOGY COMPARISON

Parameters	Parabolic Trough	Dish/Engine	Power Tower
Size	30-320 MW	5-25 kW	10-200 MW
Operating Temp. (ºC/ºF)	390/734	750/1382	565/1049
Annual Capacity Factor	23-50 %	25 %	20-77 %
Peak Efficiency	20%(d)	29.4%(d)	23%(p)
Net Annual Efficiency	11(d)-16%	12-25%(p)	7(d)-20%
Commercial Status	Prototype	Demonstration	Available
Development Risk	Low	High	Medium
Storage Available	Limited	Battery	Yes
Hybrid Designs	Yes	Yes	Yes
Cost USD/W	2,7-4,0	1,3-12,6	2,5-4,4

Table 2.2 Characteristics of solar thermal electric power systems.

	Parabolic Trough	Parabolic Dish	Power Tower
Application	Grid-connected electric plants; Process heat for industrial use.	Standalone small power system; grid support.	Grid-connected electric plants; process heat for industrial use.
Advantages	Dispatch able peaking electricity, commercially available with 4,500 GW operating experience; hybrid (solar/fossil) operation.	Dispatch able electricity, high conversion efficiencies; modularity; hybrid (solar/fossil) operation.	Dispatch able base load electricity, high conversion efficiencies; energy storage; hybrid (solar/fossil) operation.

Table 2.3 Comparison of Major Solar Thermal Technologies.

2.6 DISH-STIRLING SYSTEMS

By using dish Stirling systems electricity can be generated in kilowatts range. For this purpose, a parabolic dish is used. This dish concentrates the sunlight. To achieve high efficiency, it is necessary that parabolic dish must track the sun with high accuracy. At focal point receiver heated up to 350 degrees centigrade. This absorbed heat then run an engine, in this mechanism heat energy is converted to mechanical energy which run the engine, and this engine drive a generator to produce electricity. If sunlight is not available then other combustion heat from other sources like bio fuel or steam can also be used to drive the solar Stirling engine and generate electricity. The dish-Stirling engine has about 32% efficiency. In many countries prototype of these systems is tested successfully.

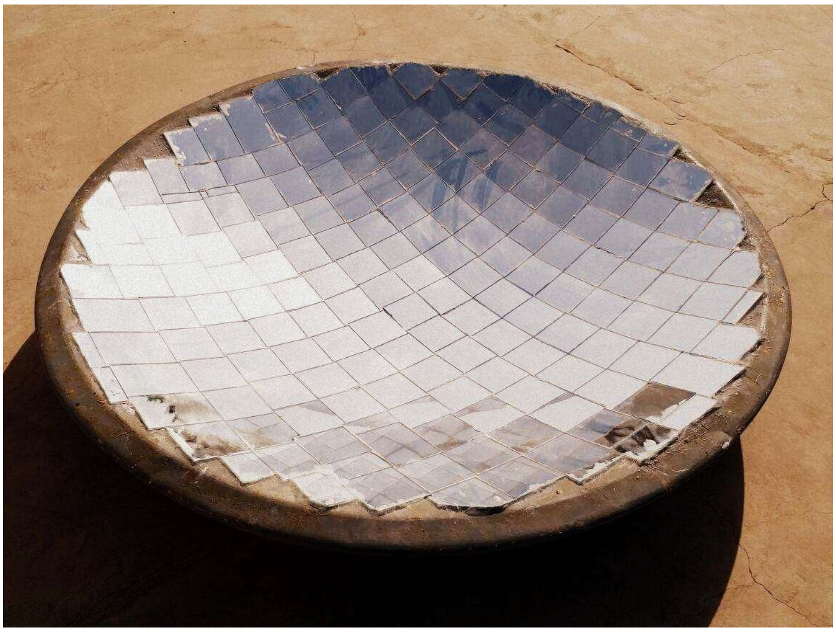


Figure 2.2 Parabolic Dish

2.6.1 BENEFITS

Solar thermal power plants create two and one-half times as many skilled, high paying jobs as do conventional power plants that use fossil fuels. California Energy Commission study shows that even with existing tax credits, a solar thermal electric plant pays about 1.7 times more in federal, state, and local taxes than an equivalent natural gas combined cycle plant. If the plants paid the same level of taxes, their cost of electricity would be roughly the same.

2.6.2 POTENTIAL

If utilized 1% of the earth's deserts to produce thermal electrical energy, then this would provide us more electricity in Pakistan then currently energy is being produced by fossil fuels. Pakistan is a very rich country so if we work and we utilized sources properly then we can our come load shedding.

2.7 REQUIREMENTS FOR OUR MODEL

The segments of our project are

- Solar Collector
- A Stirling Engine

Final design needs to be capable of producing an optimum amount of electricity. Due to unavailability of the required material the final output may deviate from actual one. The electricity is to be generated from a Stirling engine, which obtains its heat from a solar collector.

The generation of electricity for this project is to be done by harnessing the suns energy with the use of a large parabolic dish, which should track the position of the sun throughout the day.

2.8 ADVANTAGES OF STIRLING ENGINE

- They can be started by providing heat to its chamber. The heat source can be solar, geothermal, biological, nuclear sources or waste heat from industrial processes.
- Due to its unique look the bearing and seals are on the cool side of the engine, which is mostly not found in other engines.

- The lubricants are used in less quantity and will be last longer than other type of engine.
- Its mechanism is very simple and portable easily than other engine types.
- A Stirling engine maintain its internal pressure so for the properly design risk of explosion is very low.
- Stirling engine starts easily and these run more efficiently in warm weather.

2.9 DISADVANTAGES OF STIRLING ENGINES

2.9.1 SIZE AND COST ISSUE

Stirling engine require heat exchanger for both heat input and heat output so material is very costly so due to big size and material used in engine Cost of Stirling engine increased.

2.9.2 POWER AND TORQUE ISSUES

Stirling engine which run on small temperature difference they have low specific power and this is due to the heat transfer coefficient of gaseous convection. By increasing the temperature differentials output power produced increases.

- These engines are best to be used as constant speed.
- Stirling engine cannot be started immediately it requires time to warm up. It is for all type of combustion engine that they take some time for start.
- It is necessary that output power of Stirling engine must be constant, for the purpose it needs careful design,
- Changes in output power can be observed by changing the amount of working fluid. Or simply applying load on engine. This is a drawback where we need constant power output.

CHAPTER # 3

STIRLING ENGINE

3.1 INTRODUCTION

Stirling engines are external combustion engines which can function by using a wide variety of fuel sources such as a combustible gas, nuclear head, or solar energy. The heat supplied to the engine causes the working fluid to expand; thereby, moving a displacer piston. This piston then displaces the working fluid from the hot end into the cold end of the engine where the working fluid is compressed and the piston retracts. The displacer piston then moves the fluid into the hot end where it will once be expanded and then displaced into the cold end where it will compress and this cycle will continue as long the temperature difference exists. The Stirling cycle is a reversible cycle which closely follows the Carnot principal, making it a highly efficient cycle. Stirling engines are the simplest form of heat engine and are arguably the most efficient engine. The Stirling engine is noted for its high efficiency compared to steam engines, quiet operation, and the ease with which it can use almost any heat source. This compatibility with alternative and renewable energy sources has become increasingly significant as the price of conventional fuels rises, and considering concerns such as peak oil and climate change. This engine is currently exciting interest as the core component of micro combined heat and power (CHP) units, in which it is more efficient and safer than a comparable steam engine.

3.1.1 BRIEF HISTORY

In 1816, Robert Stirling invented the Stirling engine, a device with cyclic compression and expansion of the working fluid at different temperature levels. This operation, the Stirling cycle, is also known as a closed regenerative thermodynamic cycle, and a net conversion of heat to work is accomplished by the volume change regulating the flow.

3.1.2 STIRLING ENGINE CYCLE

The four thermodynamic processes that make up this Stirling cycle consists of isothermal expansion due to heat from an external source (1), constant volume heat removal (2), isothermal compression (3), and constant-volume heat addition (4); each part of the cycle is represented by the corresponding numbers in Figure 1.

FROM 1 TO 2 ISOTHERMAL EXPANSION

The heat from the regenerator and the heater, it expands forcing the light-weight displacer to the Bottom-Dead-Center (BDC) and the gas above the power piston pushes the power piston down to BDC. This is isothermal expansion, meaning the temperature of the gas does not change. This is the step of the cycle where the gas does positive work, pushing the working piston.

FROM 2 TO 3 CONSTANT VOLUME REGENERATIVE TRANSFER

No work occurs in this step. The displacer moves up to the Top Dead Center and forces the gas from hot space through the regenerator which absorbs some heat, reducing the temperature of the gas moving to cold space.

FROM 3 TO 4 ISOTHERMAL COMPRESSION'S

Both working piston and displacer move up while the working gas heat at T_C (critical temperature) is transferred to the regenerator. Therefore at the cold temperature the heat is removed from the working gas.

FROM 4 TO 1 CONSTANT VOLUME REGENERATIVE TRANSFER

The working piston and displacer are situated at the top dead center of each stroke while from the regenerator the heat is transferred to the working gas, with the increase in the temperature at constant volume from T_C to T_H (threshold temperature). There is an increase in the entropy, and internal energy, of the working gas, and no work is done.

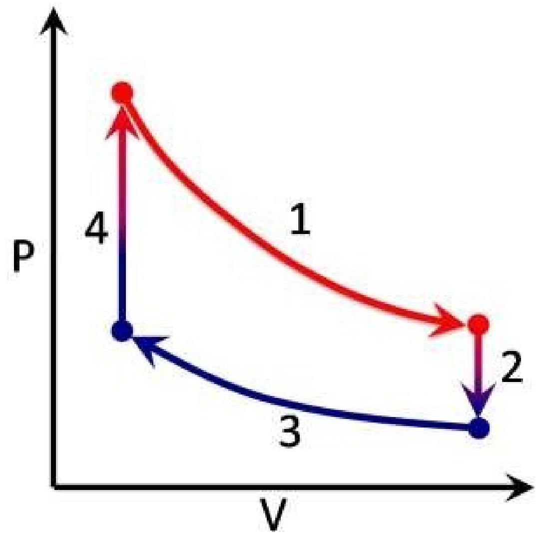


Figure 3.1 PV diagram of Idealized Stirling Cycle.

3.1.3 WORKING PRINCIPLE OF STIRLING ENGINE

Stirling engine is simply a hot air engine, which uses air as a working fluid. Air is freely available so there is no problem of costs of fluid. It is very essential to transfer heat toward the working fluid. To reduce friction or losses working fluid must be of low viscosity. These Stirling engines are generally used to convert the heat differences into useful mechanical work. They have a better impact over other engines in terms of efficiency. The limit of operation depends on the material which is used for the construction of Stirling engine.

3.1.4 ENGINE COMPONENTS:

All the processes carried in a Stirling engine are carried out by few major components. They are as follows:

3.1.4.1 DISPLACER MECHANISM:

It is enclosed in a hot chamber and moves up and down because of expansion in hot chamber and compression in the cold chamber. Through generator it moves the gas between hot and cold ends of the engine.

3.1.4.2 REGENERATOR:

When working gas is heated in displacer unit it passes through regenerator (heat sink), so the temperature of the working gas is decreased and vice versa. The regenerator basically performs the function of storing heat when working gas moves from hot to cold end and resupplying it when it moves from cold to the hot end.

3.1.4.3 WORKING GAS:

Working gas can usually be air, Helium, Hydrogen etc. As it is a closed cycle so various thermodynamic processes are being carried out.

3.1.4.4 HEAT EXCHANGERS:

If we want to transfer heat from boundary of one system to the other then heat exchangers are used. We will use two heat exchangers one will absorb and the other will reject heat from the system.

3.1.4.5 EXPANSION AND COMPRESSION MECHANISM:

Whenever the molecules of a gas are heated they start colliding with the walls of container and as a result the gas expands. The process of expansion takes place in displacer chamber (Hot chamber). When gases are heated they start collisions with one another and with the walls of hot chamber as a result their kinetic energy is shifted to the piston which moves upwards. After passing through regenerator when the gasses enter the cold chamber they contract. This contraction causes lowering of temperature and a sucking action in the cold chamber as a result piston moves downwards. Displacer cylinder is 90 degrees behind the piston extracting more work from gas.

3.2 TYPES OF STIRLING ENGINES:

There are three types of Stirling engine which are given below:

- Alpha (α) type
- Beta (β) type
- Gamma (γ) type

3.2.1 ALPHA TYPE (α):

Alpha type Stirling engine contains two power pistons in two separate cylinders, one hot and one cold. The hot cylinder is subjected to heat and the other one to cold and heat dissipation This type of engine has a high power-to-volume ratio but has technical problems due to the usually high temperature of the hot piston and the durability of its seals.

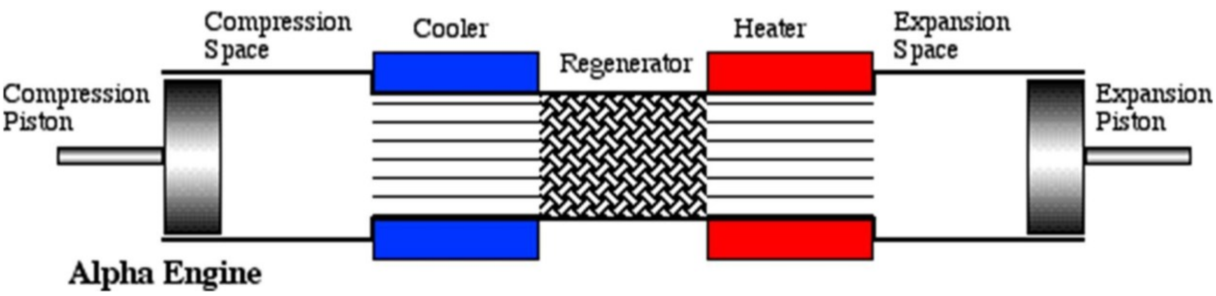


Figure 3.2 Alpha type stirlling engine

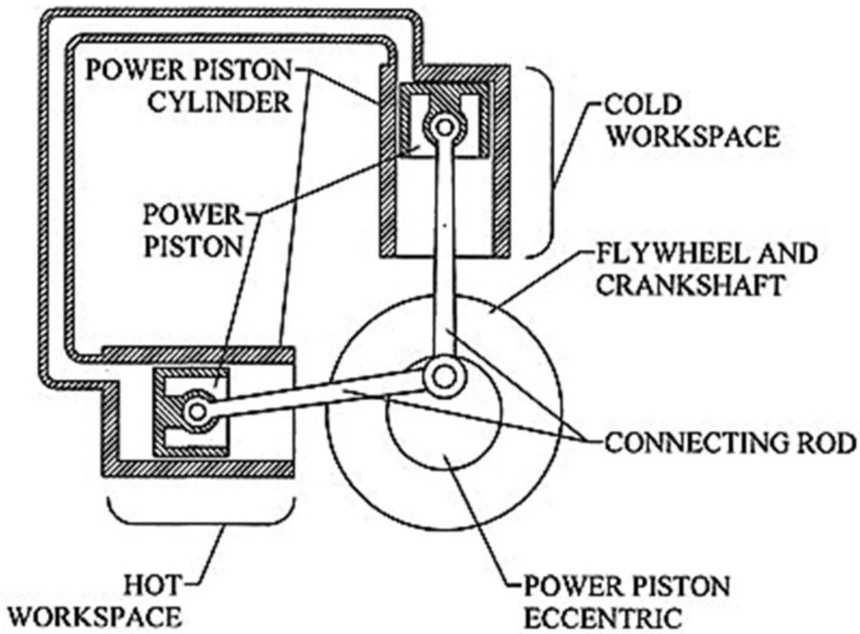


Figure 3.3 Alpha type stirlling engine

3.2.1.1 ADVANTAGES

- High power-to-volume ratio
- Relatively simple design as compared to the beta type stirling engine.

3.2.1.2 DISADVANTAGES

- Causes technical problems due to the high temperature of the hot piston
- Sealing of the hot and cold pistons is a primary problem due to dual pistons Advantages

3.2.2 BETA TYPE (β):

A Beta Stirling engine has a single power piston arranged within the same cylinder on the same shaft as a displacer piston. The displacer piston is a loose fit and does not extract any power from the expanding gas but only serves to shuttle the working gas from the hot heat exchanger to the cold heat exchanger. When the working gas is pushed to the hot end of the cylinder it expands and pushes the power piston. When it is pushed to the cold end of the cylinder it contracts and the momentum of the machine, usually enhanced by a flywheel, pushes the power piston the other way to compress the gas. It avoids all the problems faced in Alpha type. Its figure is as follows

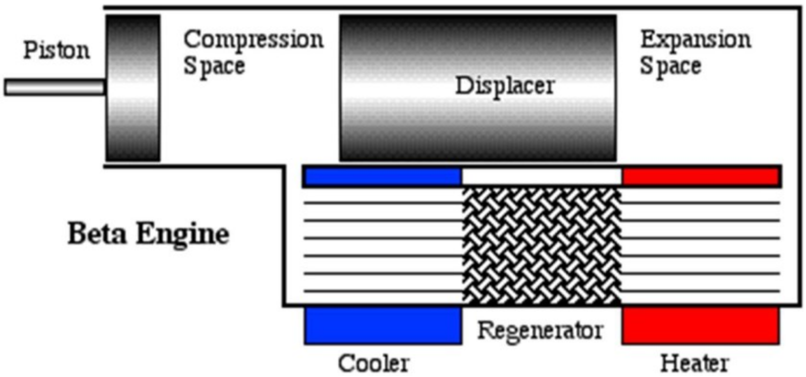


Figure 3.4 Beta type Stirling engine

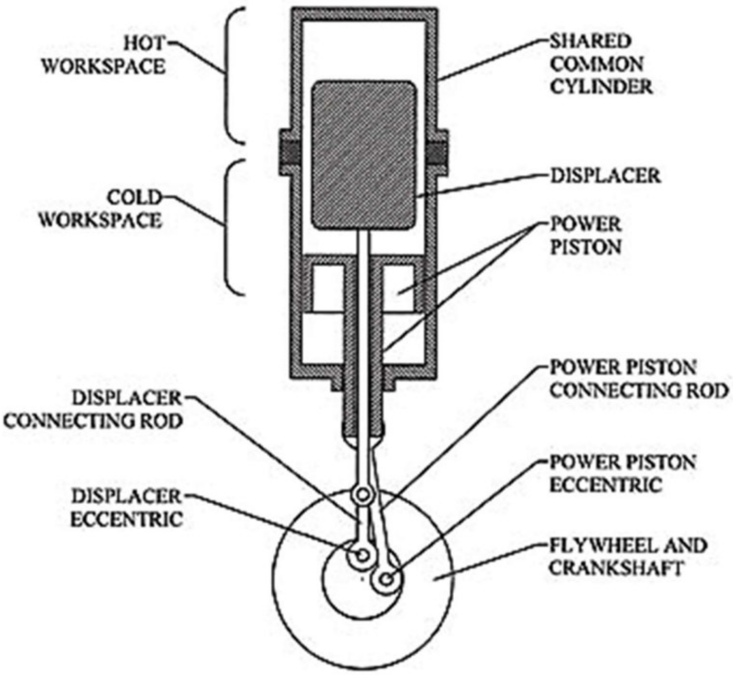


Figure 3.5 Beta type Stirling engine

3.2.2.1 ADVANTAGES

- Just one cylinder needs to be sealed.
- Beta type avoids the technical problems of hot moving seals.

3.2.2.2 DISADVANTAGES

- Containing the moving power and displacer pistons in one cylinder poses design problems.

3.2.3 GAMMA TYPE (γ):

A gamma stirling engine is simply a beta Stirling in which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder, but is still connected to the same flywheel. The gas in the two cylinders can flow freely between them and remains a single bod. Gamma type Stirling engines have power piston and displacer piston connected to the same shaft being displacer lagging 90 degrees from the power piston.

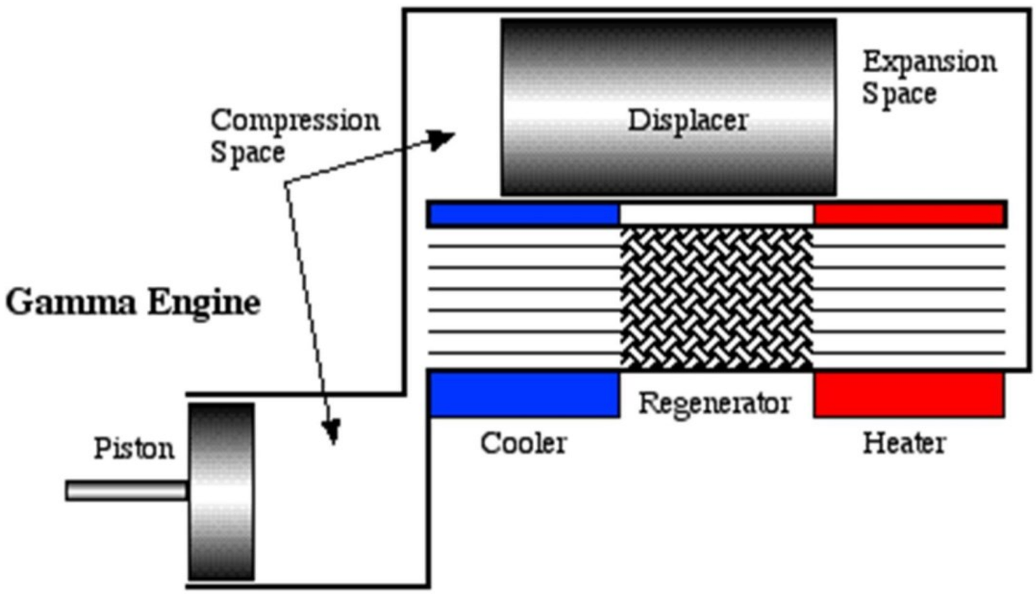


Figure 3.6 Gamma type Stirling engine

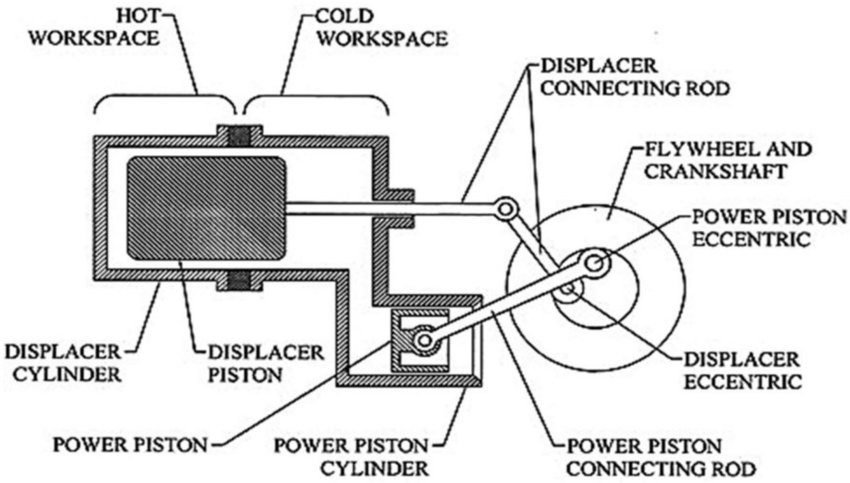


Figure 3.7 Gamma type Stirling engine

3.2.3.1 ADVANTAGES

- Mechanically simpler in design when compared with a beta type engine due to the power piston and displacer being in separate cylinders.
- Sealing is relatively easier.
- Avoids the technical problems of hot moving seals.

3.2.3.2 DISADVANTAGES

- Produces a lower compression ratio.

3.3 COMPARISON OF STIRLING ENGINE WITH AN INTERNAL COMBUSTION ENGINE

3.3.1 ADVANTAGES

- In contrast to internal combustion engines, they can use renewable heat sources more easily.
- Are quieter than internal combustion engines.
- More reliable with lower maintenance dues to lesser moving components.

- More efficient and cleaner (creation of pollutants such as NOx can be avoided).
- Since the fuel is burned slowly and constantly outside the engine, there are no explosions to muffle. Thus, there are no violent vibrations.
- A Stirling cycle is truly reversible (this means that if you heat and cool the heat exchangers of the engine you get power out or if you power the engine you get heating or cooling out).
- No valves are needed.
- A Stirling engine uses a single-phase working fluid which maintains an internal pressure closes to the design pressure, and thus for a properly designed system the risk of explosion is low. In comparison, a steam engine uses a two-phase gas/liquid working fluid, so a faulty relief valve can cause an explosion.
- Since they run without an air supply, they can be used for air-independent propulsion in submarines.
- Easy to start, though slowly after warming up.

3.3.2 DISADVANTAGES

- Lower power output as compared to an internal combustion engine of the same size.
- Gas leakage may pose design problems.
- The Stirling engine must successfully contain the pressure of the working fluid, where the pressure is proportional to the engine power output/temperature. In addition, the expansion-side heat exchanger is often at very high temperature, so the materials must resist the corrosive effects of the heat source, and have low creep.

3.4 SOLAR THERMAL CONVERSION SYSTEMS

Low-power range solar thermal conversion units consist of three main sub-systems: the solar receiver, the thermodynamic gas circuit, and the drive mechanism. Stirling engines are considered among the most effective of these units and improvements in performance can be made based on changes in the main sub-systems

The solar powered Stirling engine was patented in 1987 by Roelf J. Meijer. Using a large dish facing the sun, the rays of sunlight can be reflected onto a focus point at the center of the dish to collect solar energy as a source of heat. The heat then powers the Stirling engine connected to the solar dish collector and produces electricity, which makes the system a viable alternative energy source. The development of the solar powered Stirling engine began as Ford Motor Company obtained a worldwide exclusive license to research almost all applications of the Stirling engine from N.V. Philips of the Netherlands. Philips worked on making Stirling engines for the Ford Torino vehicles, however, the project ended early and the work continued instead at Stirling Thermal Motors, Inc. The solar powered Stirling engine has other applications as a pump, which is important as it is cost effective and can be used for water pumping in areas of the world where there is low access to clean water. Pumping systems employed in sunbelt countries have a maximum water cost target of 6 cents/m^3, as set by the World Bank based on their study demonstrating photovoltaic pumping systems currently cost 8.4 cents/m^3 and gasoline pumping systems at 8.58 cents/m^3. Sunvention Sunpulse Water has designed and constructed a prototype solar thermal water pump, which consists of a solar collector directly coupled to a slow-speed Stirling engine that can be coupled to the water pump, or anything else that requires mechanical power. TÜV labs assessed the Sunvention system and found it works at a cost of 2.4 cents/m^3 – an amount that meets the World Bank target. This means there are many applications for the solar powered Stirling engine outside of electricity production and water pumping, since it can serve as an air pump for fish farms or to fulfill mechanical requirements such as milling, grinding, and compressing.

CHAPTER#4

SOLAR THERMAL POWER TECHNOLOGIES & THEIR SIGNIFCANCE

4.1 INTRODUCTION

Solar thermal power generation systems capture energy from solar radiation, transform it into heat, and generate electricity from the heat using steam turbines, gas turbines, Stirling engines, or pressure staged turbines.

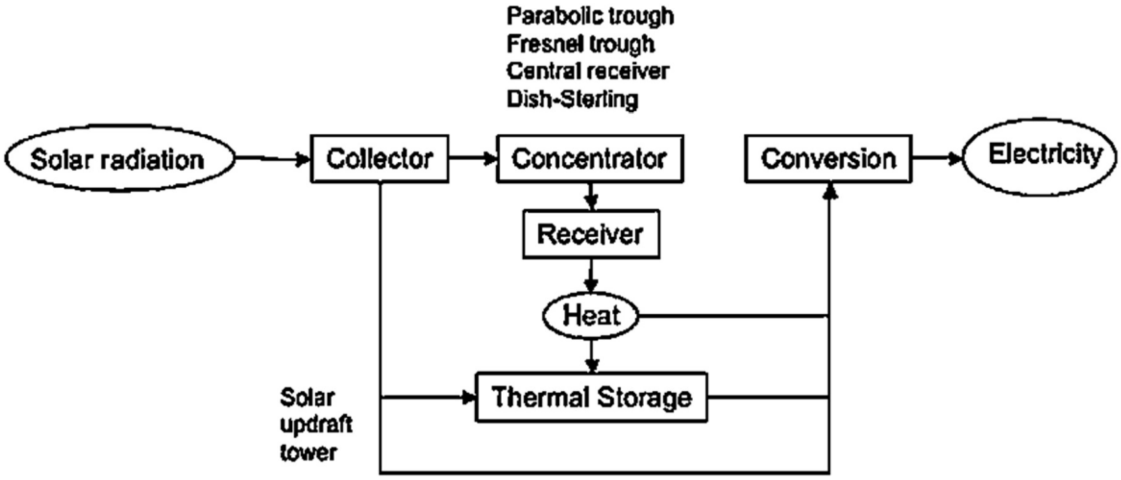


Figure 4. 1 Schematic illustration of the component parts of solar thermal power plants

The four main types of solar thermal power plants developed and tested so far are:

- Parabolic trough and Fresnel trough technology
- Central receiver system (also called power tower or solar tower)
- Dish-Stirling system
- Solar updraft tower plant

Parabolic and Fresnel trough, central receiver, and dish-engine systems concentrate the sunlight to gain higher temperatures in the power cycle. The primary resource for concentrating solar power (CSP) technology is the direct solar irradiance perpendicular to a surface that is continuously tracking the sun (direct normal irradiance, DNI). CSP systems have their highest potential in the "sun belt" of the earth, which is between the 20th and 40th degree of latitude south and north. Solar updraft towers do not concentrate the sunlight. They use the direct fraction of the sunlight as well as the diffuse fraction. As a consequence, the working temperature is much lower than those of concentrating systems, and thus the efficiency.

The electricity is produced by different ways:

- Troughs and central receivers usually use a steam turbine to convert the heat into electricity. As heat transfer fluids oil, molten salt, air, or water can be used. Central receivers can achieve very high operating temperatures of more than 1,000 °C enabling them to produce hot air for gas turbines operation combined with downstream steam turbine operation resulting in high conversion efficiencies.
- Dish-Stirling systems can use an engine at the focus of each dish or transport heat from an array of dishes to a single central power-generating block.
- Solar updraft towers work with a central updraft tube to generate a solar induced convective flow which drives pressure staged turbines.

4.1.1 PARABOLIC AND FRESNEL TROUGH TECHNOLOGY:

Parabolic trough systems consist of trough solar collector arrays and a conventional power block with steam turbine and generator. A heat transfer fluid, currently synthetic thermo oil, is pumped through the collector array and heated up to 400 °C. This oil is used to produce steam in heat exchangers before being circulated back to the array. The steam is used in a conventional steam turbine-based power plant.

Figure 4.2 Parabolic Trough System

In general, parabolic trough systems using thermo oil can be considered as most mature CSP technology. Further developments of the original system are aiming at the replacement of the synthetic heat transfer oil with direct steam or with molten salt. Direct steam generation (DSG) allows the collection of energy at higher temperatures as well as the elimination of one heat exchange step which increases the overall efficiency of the plant. Furthermore, it avoids the need to replace the heat transfer fluid as it is necessary in case of thermo oil and it avoids the use of energy intensive manufactured and toxic oil. Both improve the plant's economic and ecological balance. The first DSG plant commercially being built will be the 50 MW project Andasol 3 in Spain. The utilization of molten salts as primary fluid shows similar advantages like the increase of the solar field operating temperature and therefore a better efficiency, and the elimination of the heat exchanger in case of using a molten salt storage system. On the other hand, the solar field and the heat transfer fluid require continuous heat tracing to avoid refreezing of the salt. Currently there are only few studies concerned with this innovation.

The Fresnel trough simplifies the concentration system by using a plain surface of nearly flat mirror facets, which track the sun with only a single axis and approximate the classic parabolic mirror. The efficiency is smaller than with a classic parabolic mirror. The idea is that the lower costs over-compensate the energy losses in the final economic assessment.

Figure 4.3 Fresnel Trough

4.1.2 CENTRAL RECEIVER SYSTEMS:

Central receiver (CR) systems consist of a field of heliostats (almost plane mirrors), a tower, and a receiver at the top of the tower. The field of heliostats all move independently to one another and beam the solar radiation to one single point, the receiver. Heliostat fields can either surround the tower or be spread out on the shadow side of the tower. Two generic approaches to heliostat design have been used: a plane structure and a "stretched membrane" approach. Major investigations during the past 20 years have focused on four heat transfer fluid systems: water/steam, molten salt, atmospheric air, and pressurized air.

Central receivers have the advantage that the energy conversion takes place at a single fixed point, which reduces the need for energy transport. By the high concentration factor operation temperatures of more than 1,000 °C can be reached. This rises the conversion efficiency and allows for advanced energy conversion systems (combined cycle instead of steam cycle). Figure 2.2 shows the 11 MW PS 10 tower power system operated near Sevilla. One of the newest developments is the "beam-down" concept proposed and tested partly by the Weizmann Institute of Science in Israel. Rather than converting the concentrated solar energy at the top of the tower, a hyperbolically shaped secondary mirror directs the converging radiation vertically downward to a focal point at the bottom of the tower.

Figure 4.4 Central Receiver System

One of the newest developments is the "beam-down" concept proposed and tested partly by the Weizmann Institute of Science in Israel. Rather than converting the concentrated solar energy at the top of the tower, a hyperbolically shaped secondary mirror directs the converging radiation vertically downward to a focal point at the bottom of the tower.

The largest central receiver solar system formerly realized was the 10 MW "Solar Two" plant in southern California. In February 2007 the 11 MW solar thermal power plant PS10 started its operation in Southern Spain as the first central receiver which has been built for the last years. Currently being built in Spain is the 15 MW power tower SolarTres equipped with a 16 hours thermal storage. Worldwide projects with a total capacity of 566 MW are planned, therein the 2 x 20 MW power tower PS20 as a successor of PS10 and a 400 MW power tower announced by Bright Source Energy for California.

4.1.3 DISH-ENGINE SYSTEMS:

Paraboloidal dish concentrators focus solar radiation onto a point focus receiver. Like parabolic trough systems they require continuous adjustment of its position to maintain the focus. Dish-based solar thermal power systems can be divided into two groups: those that generate electricity with engines at the focus of each dish and those that transport heat from an array of dishes to a single central power-generating block. Stirling engines are well suited for construction at the size needed for operation on single-dish systems, and they function with good efficiency. Dish-stirling units of 25 kW have achieved overall efficiency of close to 30%. This represents the maximum net solar-to-electricity conversion efficiency achieved by any non-laboratory solar energy conversion technology.

Figure 4.5 Solar Dish Engine System

4.1.4 SOLAR UPDRAFT TOWER PLANT:

A solar updraft tower plant (sometimes also called solar chimney) is a solar thermal power plant working with a combination of a non-concentrating solar collector for heating air and a central updraft tube to generate a solar induced convective flow. This air flow drives pressure staged turbines to generate electricity. The collector consists of a circular translucent roof open at the periphery and the natural ground below. Air is heated by solar radiation under this collector. In the middle of the collector there is a vertical tower with large inlets at its base. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter.

Figure 4.6 Solar Updraft Tower

Continuous 24-hour operation can be achieved by placing tight water-filled tubes or bags under the roof. The water heats up during day-time and releases its heat at night. Thus, solar radiation causes a constant updraft in the tower (although this storage system has never been installed or tested up to now). The energy contained in the updraft is converted into mechanical energy by pressure-staged turbines at the base of the tower, and into electrical energy by conventional generators.

An experimental plant with a power of 50 kW was established in Manzanares (Spain) in 1981/82. For Australia, a 200 MW solar updraft tower, shown in Figure 2.4, was planned but cancelled in summer 2006. Currently a 40 MW updraft tower project is announced in

Spain (Campo3 2006). Due to the uncertain perspectives of this technology, the absence of a reference project, and therefore the lack of cost and material data the solar updraft tower is not considered furthermore in this study.

4.2 TECHNOLOGY COMPARISON:

Here is a brief technology comparison of all solar thermal power technologies:

Technology	Typical Operating Temperature	Concentration Ratio	Tracking	Net. Efficiency	Type of Operation	Installed Capacity	Annual output
	C			%		MW	GW
Parabolic + Fresnel trough	260-400	80-200	One-axis	9-14	Commercial	354	988
Central receiver	500-800	500-1000	Two-axes	13-18	Commercial	10250	-
Parabolic Dish	500-1200	800-8000	Two-axes	15-24	demo	-	-

Table 4. 1 Technology Comparison

4.3 WEAK POINTS AND BARRIERS:

- Solar thermal power plants currently cause high electricity generation costs which have to be decreased by technological innovations, volume production, and scaling up to bigger units.

- Although there is a huge solar irradiation supply only locations with irradiations of more than 2,000 kWh/m^2, is suited to a reasonable economic solar thermal performance.

4.4 STRONG POINTS AND DIFFUSION FACTORS:

- An advantage of solar thermal systems is their relatively high energy density. With 200 - 300 GWh electricity produced per km2 land use they require the lowest land use per unit electricity produced among all renewables.

- Solar thermal power plants can store the primary energy in concrete, molten salt, phase change material, or ceramic storage systems and produce electricity by feeding steam turbines with the stored heat over night. This means that balancing power can be delivered and therefore solar thermal power plants could be used as a back-up system even for intermittent photovoltaics and wind energy.

- Solar thermal power plants need big areas but there are huge areas available especially in the desert regions of the earth. For example, to meet Europe's electricity demand (about

- 3,500 TWh/a) only by solar thermal electricity, an area of only 120 x 120 km in a North African desert would be necessary (that means 0.14% of the Sahara's area).

- Solar thermal power plants can be operated as co-generation plants by using its steam not only for electricity generation but also for steam delivery, cooling, and desalting water.

CHAPTER#5

SOLAR POTENTIAL OF HYDERABAD

5.1 SOLAR POTENTIAL OF PAKISTAN.

Pakistan has a unique geographical location, being situated at a point where it receives maximum solar radiations throughout the year. Some areas of southern Pakistan like Quetta, areas of central and southern Punjab like Lahore, Faisalabad, Multan, Bahawalpur, and Rahimyar Khan receive the maximum of the solar radiations throughout the year. Pakistan usually receives 6.8 to 8.3 KMJ/m^2 per year and an average sunshine is almost 7-9 hours daily.

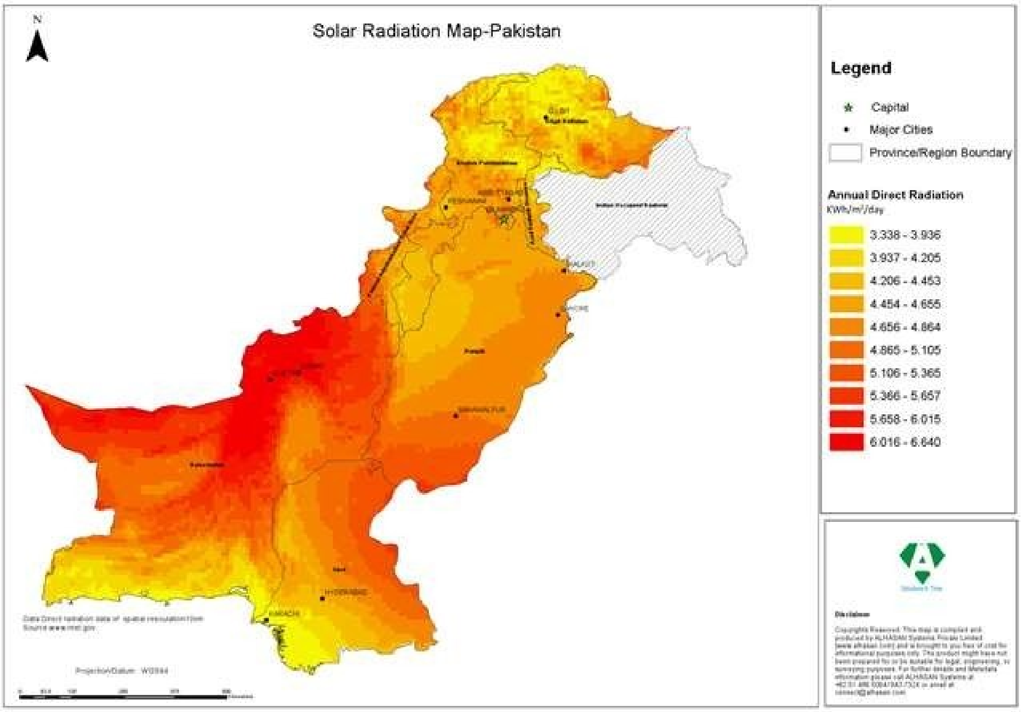


Figure 5.1 Solar Radiation Map of Pakistan

Pakistan has a huge potential for converting the solar energy into useful and beneficial means. This solar energy can be harvested to produce electricity to overcome the energy crisis of Pakistan. According to Energy Book Pakistan 2004-2005, the 0.25 % of solar irradiance falling only on Baluchistan province will be sufficient to meet the current energy crisis of the country. Insolation is very high in Pakistan, at 5.3 kWh/m²/day. Pakistan has also set a target to add 5% approximately 10,000 MW electricity through renewable energies by year 2030 besides replacement of 5% diesel with bio-diesel by year 2015 and 10% by 2025.

5.2 HISTORY OF HYDERABAD

Hyderabad is a city located in Sindh province of southern Pakistan. Hyderabad is the 6th largest city in Pakistan and the 2nd largest in the province of Sindh. The City of Hyderabad served as the capital of Sindh province. From 1947 to 1955, which was later dissolved and one unit was formed named West Pakistan City also served as capital during Kalhoro regime

The independence of Pakistan in 1947 saw the influx of Muslim Urdu-speaking Muhajirs from India fleeing from anti-Muslim pogroms. Muhajirs mainly live in Latifabad and Sindhi mainly live in Qasimabad areas. The city therefore has cosmopolitan atmosphere with multiethnic and multicultural communities. Hindus account for the largest religious minority forming 5% of the total population of the city. While Christians account for 1% of the total population, Hyderabad is the seat of a Diocese of the Church of Pakistan and has five churches and a cathedral.

5.3 GEOGRAPHY AND CLIMATE

Hyderabad is located on the east bank of the Indus River with an elevation of 13 metres (43 ft). Hyderabad has a hot desert climate, with warm conditions year-round. The period from mid-April to late June (before the onset of the monsoon) is the hottest of the year, with highs peaking in May at 41.4 °C (106.5 °F). During this time, winds that blow usually bring along clouds of dust, and people prefer staying indoors in the daytime, while the breeze that flows at night is more pleasant. Winters are warm, with highs around 25 °C (77 °F), though lows can often drop below 10 °C (50 °F) at night. The highest temperature of 48.5 °C (119 °F) was recorded on 7 June 1991, while the lowest temperature of 1 °C (34 °F) was recorded on 8 February 2012.

In recent years, Hyderabad has seen great downpours. In February 2003, Hyderabad received 105 millimetres (4.13 in) of rain in 12 hours, leaving many dead. The years of 2006 and 2007 saw close contenders to this record rain with death tolls estimated in the hundreds. The highest single-day rain total of 250.7 millimetres (9.87 in) was recorded on 12 September 1962, while the wettest month was September 1962, at 286 millimetres (11.26 in).

5.4 SOLAR POTENTIAL OF HYDERABAD

Pakistan is a solar rich country and is blessed with abundant solar radiation due to its ideal location in sunny belt. Solar energy is available for more than 300 days a year in Pakistan with about 6-8 effective days light hours. Solar energy available in Pakistan can fulfill energy shortfall if managed properly. Hyderabad is located at 25.367 °N latitude and 68.367 °E longitude since it is also situated in the sunny zone of the province, the potential of Hyderabad can be harnessed for utilization of available solar energy.

Month	Jan	Feb	Mar	Apr	May	Jun
Record high °C (°F)	33.3 (91.9)	38.2 (100.8)	43.4 (110.1)	46.0 (114.8)	48.4 (119.1)	48.5 (119.3)
Average high °C (°F)	25.0 (77)	28.1 (82.6)	33.9 (93)	38.9 (102)	41.6 (106.9)	40.2 (104.4)
Average low °C (°F)	11.1 (52)	13.6 (56.5)	18.5 (65.3)	23.0 (73.4)	26.2 (79.2)	28.1 (82.6)
Record low °C (°F)	3.3 (37.9)	4.0 (39.2)	9.0 (48.2)	12.0 (53.6)	19.0 (66.2)	20.0 (68)
Mean monthly sunshine hours	272.8	257.1	288.3	288.0	313.1	279.0

Month	Jul	Aug	Sep	Oct	Nov	Dec
Record high °C (°F)	45.5 (113.9)	43.9 (111)	45.0 (113)	44.0 (111.2)	41.0 (105.8)	36.0 (96.8)
Average high °C (°F)	37.4 (99.3)	36.3 (97.3)	36.8 (98.2)	37.2 (99)	31.9 (89.4)	26.3 (79.3)
Average low °C (°F)	27.8 (82)	26.7 (80.1)	25.3 (77.5)	22.3 (72.1)	17.3 (63.1)	12.5 (54.5)
Record low °C (°F)	21.4 (70.5)	22.8 (73)	20.6 (69.1)	15.0 (59)	6.0 (42.8)	3.0 (37.4)
Mean monthly sunshine hours	235.6	251.1	285.0	306.9	279.0	272.8

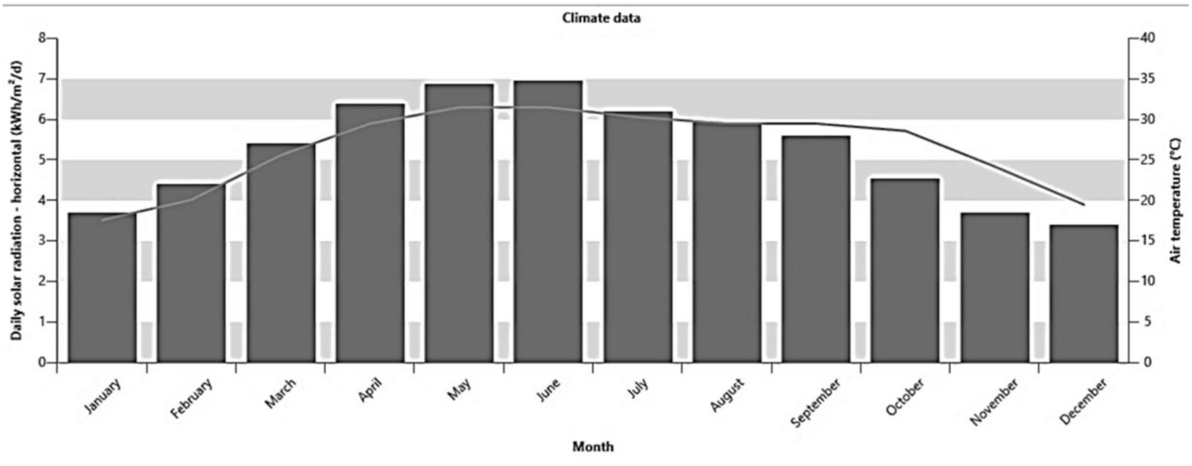
Table 5.1 Climate data for Hyderabad

5.4.1 COLLECTION OF DATA

The selection of site always plays a vital role in any design criteria; and it includes the information about temperature, pressure, wind velocity, global radiation and angle of incident of solar radiation. The solar data for Hyderabad was obtained from internet with the help of simulation software RET screen and PVSYST 5.0 design criteria because lowest temperature during the year. Hence this day is selected as the design day. The monthly average daily global solar radiation H, the extraterrestrial solar radiation H_o, diffuse solar radiation H_d, Clearance index value K_T, temperature and Wind velocity for Hyderabad are shown in table below.

Month	Extra-terrestrial Solar Radiation (H_o)	Global Solar Radiation (H)	Diffuse Solar Radiation (H_d)	Clearance Index (K_T)	Temperature (°C)	Wind Velocity (m/s)
January	6.5	4.08	1.41	0.66	19.5	2.39
February	7.8	4.53	2.05	0.68	22.3	2.61
March	9.4	5.30	2.61	0.65	26.4	2.90
April	10.3	6.11	2.92	0.69	29.0	3.80
May	10.9	6.18	3.13	0.64	30.8	4.99
June	11.1	6.04	3.36	0.62	31.1	5.10
July	10.9	4.77	2.96	0.57	30.3	5.20
August	10.5	4.75	2.92	0.50	29.1	4.89
September	9.5	5.61	2.68	0.62	28.9	4.29
October	8.1	5.15	2.00	0.68	29.1	2.51
November	6.8	4.15	1.67	0.72	24.9	1.90
December	6.2	3.62	1.46	0.69	20.9	2.20

Table 5.2 Extraterrestrial Radiations, Global Radiations, Diffuse Solar Radiations, Temperature and Wind Velocity for Hyderabad



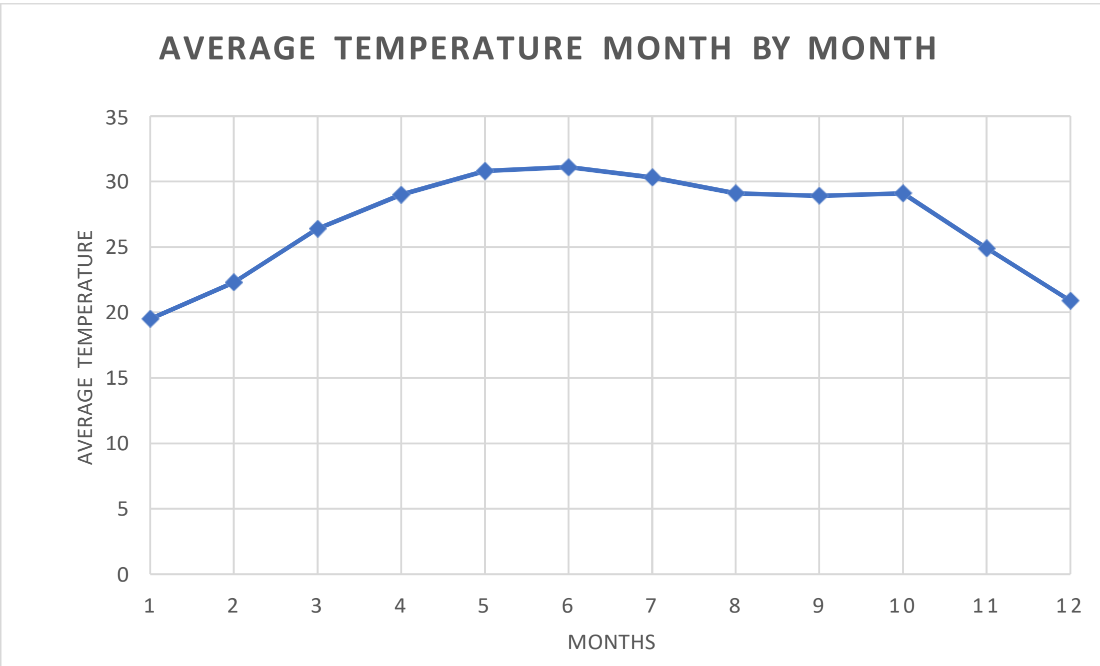
Graph 5. 1 Climate data for Hyderabad, Pakistan

Month	Air temperature °C	Relative humidity %	Precipitation mm	Daily solar radiation - horizontal kWh/m²/d
January	17.6	34.4%	4.61	3.70
February	20.1	32.8%	6.27	4.42
March	25.6	32.1%	6.72	5.41
April	29.5	36.3%	4.07	6.41
May	31.5	44.7%	7.75	6.88
June	31.5	55.7%	23.81	6.98
July	30.3	65.3%	99.56	6.20
August	29.5	65.5%	88.86	5.95
September	29.5	55.7%	17.44	5.62
October	28.6	37.0%	8.26	4.54
November	24.2	30.5%	1.48	3.70
December	19.5	30.4%	12.08	3.42
Annual	**26.5**	**43.4%**	**280.91**	**5.27**

Figure 5.2 Climate data for Hyderabad, Pakistan

Month	Wind speed (m/s)	Earth temperature (°C)	Heating degree-days 18 °C (°C-d)	Cooling degree-days 10 °C (°C-d)
January	3.2	19.3	12	236
February	3.4	22.6	0	283
March	3.5	29.7	0	484
April	3.7	34.5	0	585
May	4.2	36.5	0	667
June	4.5	36.4	0	645
July	4.0	34.4	0	629
August	3.5	33.4	0	605
September	3.4	33.7	0	585
October	3.0	32.2	0	577
November	2.8	26.6	0	426
December	3.1	21.0	0	295
Annual	**3.5**	**30.1**	**12**	**6,014**

Figure 5.3 Climate data for Hyderabad, Pakistan



Graph 5.2 Avg. Temperature v/s Month

In July and August, diffuse radiation is higher in Hyderabad, varying in between 35% to 53% as shown. It appears that solar technology can be utilized efficiently all year round.

The direct solar radiation available in these cities can be used efficiently. The cities like Karachi and Hyderabad observe the most direct solar radiation during the year, except during the monsoon months of July and August.

CHAPTER#6

CALCULATIONS

6.1 DESIGN OF SOLAR DISH

When parallel rays of sunlight fall on an aligned parabolic mirror, they will be reflected towards a single point known as focus.

The basic shape of a parabola is derived from the equation:

$y^2 = 4ax$ ----- (i)

Where y represents the distance away from the mirror center and x represents the 'height above' the center. The constant 'a' is known as the focal length.

Focal length: - The distance from the origin to the focus point.

6.1.1 SIZE OF PARABOLIC DISH

To determine the size of parabolic dish to be able to provide enough solar energy to operate 37W Stirling engine which is to be mounted on the focal point of dish.

Efficiency of Stirling Engine => η = 30%

We know that

$$\text{Input Energy} = \frac{\text{Power Output}}{\eta}$$

$power = 37 watts$

$$\text{Input Energy} = \frac{37}{0.30}$$

Input Energy = $123.4W$

Collector Efficiency => $\eta_{collector}$ = 70%

$$\text{Solar Energy Required} \Rightarrow \frac{123.4W}{0.70} = 176W$$

This is the needed solar energy.

Available Solar Energy in Hyderabad = $208 W/m^2$ (determined using solar map of Pakistan)

$$\text{Dish Area} = \frac{\text{Solar Energy Required}}{\text{Available Solar Energy}}$$

$$\text{Dish Area} = \frac{176}{208}$$

Dish Area = $0.846 m^2$

$$\text{Area} \Rightarrow \frac{\pi}{4} d^2$$

$$\text{Aperture Diameter} \Rightarrow \sqrt{\frac{4}{\pi} \times 0.846}$$

$D = 1.04m$

Hence, we selected dish size of 1.2m around 4ft which was nearest size of dish to our calculations that was available in the market. After buying the dish we had to choose from aluminum or glass as reflector material. We opted for glass keeping in mind the average available solar irradiation of Hyderabad region, where glass would be more effective than aluminum.

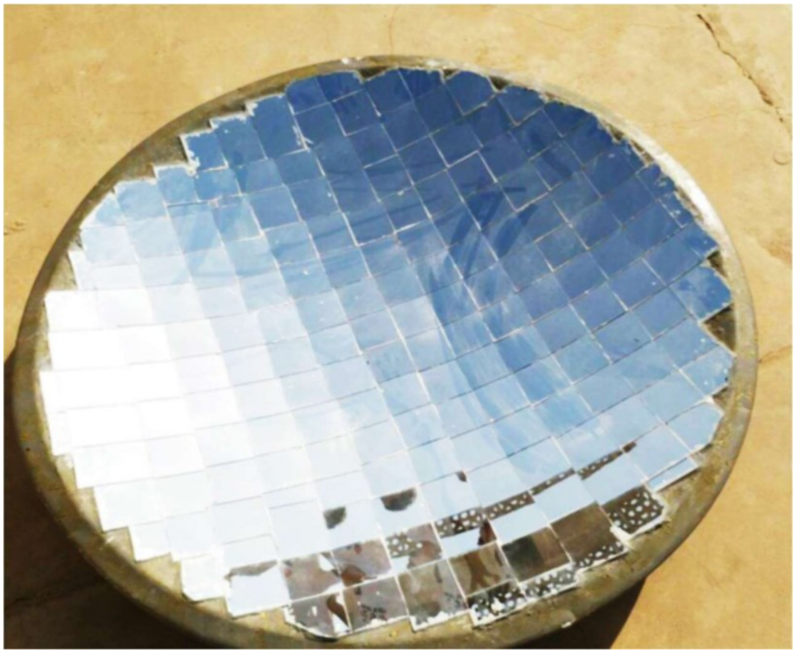


Figure 6.1 Dish covered with glass pieces

6.1.2 DETERMINING THE FOCAL LENGTH OF A PARABOLIC DISH

Focal Length = a, Depth = x, Radius = r => $\frac{D}{2}$

$$a = \frac{r^2}{4x}$$

$$D = 1.2192m \Rightarrow r = 0.6096m$$
$$x = 0.1778m$$

$$a = \frac{(0.6096)^2}{4(0.1778)}$$
$$a = 0.5225m$$

The focal length of our parabolic dish came out to be around 0.5225m or 1.71ft.

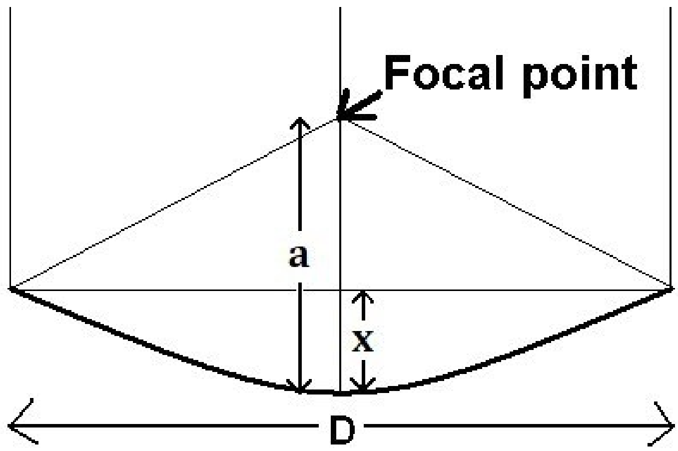


Figure 6.2 Parabola

6.2 DESIGN AND ANALYSIS OF STIRLING ENGINE:

Stirling Engine used is Gamma type stirling engine of 37 W. We have chosen gamma type stirling engine because of its simple and easy configuration and design.

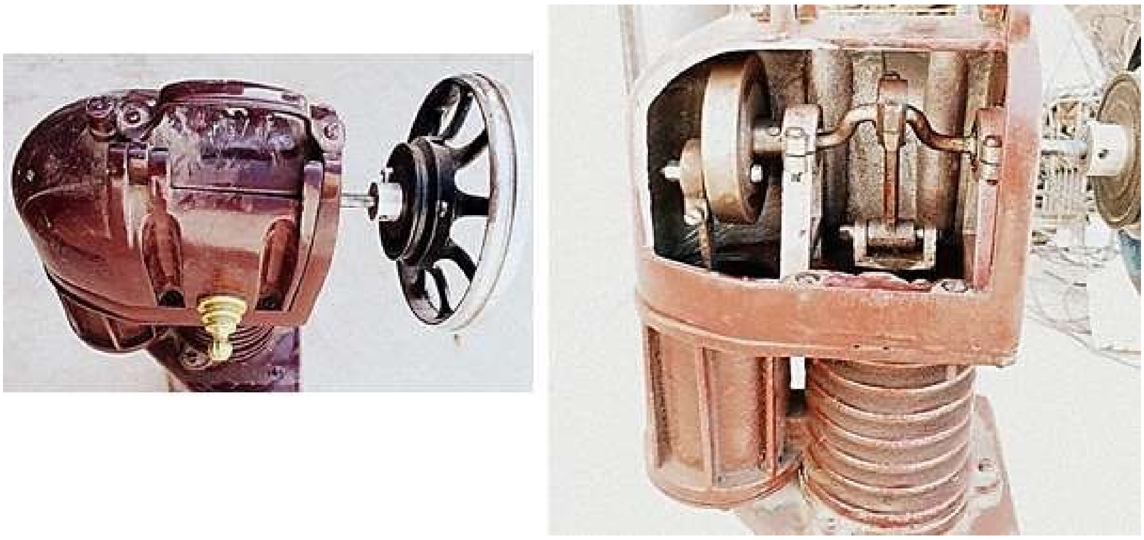


Figure 6.3 37 watts Stirling Engine

Engine Dimensions

1.	Engine Power	37 Watt
2.	Engine Volume	58cc
3.	Engine Speed	180-214 rpms
4.	Swept Volume	$55cm^3$
5.	Working fluid	Air (Nitrogen)

Table 6.1 Engine Dimensions

The power from stirling engine can be estimated using two methods.

1. Beale Number B_n
2. West Number W_n

6.2.1 Beale Number Bn:

In mechanical engineering, the Beale number is a parameter that characterizes the performance of Stirling engines. It is often used to estimate the power output of a Stirling engine design. For engines operating with a high temperature differential, typical values for the Beale number range from 0.11 to 0.15, where a larger number indicates higher performance.

The Beale number can be defined in terms of a Stirling engine's operating parameters:

$$B_N = \frac{Wo}{P \cdot V \cdot F}$$

where:

- B_n is the Beale number
- Wo is the power output of the engine (watts)
- P is the mean average gas pressure (Pa) or (MPa, if volume is in cm^3)
- V is swept volume of the power piston(m^3) or (cm^3, if pressure is in MPa)
- F is the engine cycle frequency (Hz)

6.2.2 Estimating Stirling Engine Power Using B_n:

To estimate the power output of an engine, nominal values are assumed for the Beale number, pressure, swept volume and frequency, then the power is calculated as the product of these parameters, as follows:

$$W_O = B_N \cdot P \cdot V \cdot f$$

$\text{Bn} = 0.12$ (Assumed)

$\text{P} = 0.7 \text{ MPA}$

$\text{f} = 3.333 \text{ Hz}$ $(200 rpms)$

$\text{V} = 55 \text{ cm}^3$

$W_O = (0.12)(0.7)(55)(3.33)$

$W_O = 15.3846 \text{ W} \approx 15.4 \text{ W}$

6.2.3 West Number W_n

The West number is an empirical parameter used to characterize the performance of Stirling engines and other Stirling systems. It is very similar to the Beale number where a larger number indicates higher performance; however, the West number includes temperature compensation. The West number is often used to approximate of the power output of a Stirling engine.

The West number may be defined as:

$$W_n = \frac{W_O}{PVf} \cdot \frac{(T_H + T_K)}{(T_H - T_K)} \Rightarrow W_n = B_n \frac{(T_H + T_K)}{(T_H - T_K)}$$

Where:

- **W_n** is the West number
- **W_o** is the power output of the engine (watts)
- **P** is the mean average gas pressure (Pa) or (MPa, if volume is in cm^3)
- **V** is swept volume of the expansion space (m^3) or (cm^3, if pressure is in MPa)
- **f** is the engine cycle frequency (Hz)
- **T_H** is the absolute temperature of the expansion space or heater (kelvins)
- **T_K** is the absolute temperature of the compression space or cooler (kelvins)
- **Bn** is the Beale number for an engine operating between temperatures T_H and T_K

When the Beale number is known, but the West number is not known, it is possible to calculate it. First calculate the West number at the temperatures T_H and T_K for which the Beale number is known, and then use the resulting West number to calculate output power for other temperatures.

T_H = 250 °C => 523 K

T_K = 40 °C => 313 K

Wn = (0.12)((523 + 313)/(523 - 313)

Wn = 0.4777

6.2.4 Estimating Stirling Engine Power Using Wn:

To estimate the power output of a new engine design, nominal values are assumed for the West number, pressure, swept volume and frequency, and the power is calculated as follows:

$$W_O = W_n PVf \frac{(T_H - T_K)}{(T_H + T_K)}$$

Wo = (0.4777)(0.7)(55)(3.33) *((523 - 313)/(523 + 313))

= 15.4002558 W $\approx$ 15.40 W

6.3 RESULTS & CONCLUSION

Engine power was estimated using two methods i.e. Beale number B_n and West number W_n. A power of approximately 15.4 watts was obtained because the rpm observed were around 180-200 rpm, operating on solar energy. The fabricated engines maximum power producing capacity is 37 watts and the group was able to produce 15.4 watts using solar energy, which accounts for 41.62% efficiency. Although improvement in the results can be obtained by applying some modifications in the system as using a Solar Tracking System for solar dish concentrator which in turn would increase efficiency of the system.

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