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STUDY OF VARIOUS ALTERNATIVE ENERGY SOURCES FOR THE STIRLING ENGINE

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THESIS
Abstract

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Abstract (NOTE: write/insert all your text in the grey box below, also if you use copy + paste)

The world's ever-increasing energy demand, coupled with the negative environmental impact of conventional energy sources, has led to the search for alternative and sustainable energy sources. The Stirling engine, known for its high efficiency and low emissions, is a promising technology that can use a variety of heat sources to produce mechanical work. This study aims to investigate various alternative energy sources that can be utilized with the Stirling engine, including solar, geothermal, biomass, and waste heat.

The research includes a review of existing literature and experimental studies that have explored the use of alternative energy sources for Stirling engines. The findings of this study will contribute to the understanding of the potential of various alternative energy sources for powering Stirling engines, and will provide insights into the feasibility of implementing this technology in practical applications. This research could lead to the development of new and sustainable energy sources that can reduce the world's dependence on non-renewable energy sources and mitigate the environmental impact of energy production.

Keywords

Alternative energy sources; Stirling engine; Renewable energy; Solar power; Biomass energy; Geothermal energy; Waste heat recovery; Thermoacoustic power

CONTENTS

1 INTRODUCTION

The world's growing energy demands have led to a rapid depletion of traditional energy sources, which has resulted in an increased demand for sustainable and renewable energy solutions. One such solution is the Stirling engine, which is an efficient and versatile engine that can generate power using various energy sources. The Stirling engine operates by converting thermal energy into mechanical work, and it is known for its reliability and efficiency. However, its use has been limited to traditional energy sources such as coal, oil, and gas, which are becoming increasingly unsustainable due to their negative environmental impact. (Organ, 2013)

To address this issue, researchers have been exploring alternative energy sources that can be used to power the Stirling engine. These alternative energy sources include solar energy, geothermal energy, and biomass energy. This study aims to evaluate the feasibility and effectiveness of these alternative energy sources for powering the Stirling engine.

Background:

The Stirling engine was invented by Robert Stirling in 1816, and it operates on the principle of cyclic compression and expansion of a gas (typically air) at different temperature levels. The Stirling engine has several advantages over other heat engines, such as the internal combustion engine and the steam engine. It has a higher efficiency, lower emissions, and operates with less noise and vibration.

However, the use of the Stirling engine has been limited to traditional energy sources such as coal, oil, and gas. The depletion of these energy sources has led to an increased demand for alternative energy sources that are sustainable and renewable. Therefore, researchers have been exploring the use of alternative energy sources for powering the Stirling engine.

Solar Energy:

Solar energy is a renewable energy source that is obtained from the sun's radiation. It is abundant and free, and it has the potential to provide a significant amount of energy. The Stirling engine can be powered by solar energy through the use of solar collectors, which convert solar radiation into thermal energy. The thermal energy is then used to power the Stirling engine.

The use of solar energy for powering the Stirling engine has several advantages. It is clean, renewable, and does not produce any emissions or pollution. It is also abundant and can be harnessed in almost every part of the world. However, the use of solar energy has some limitations. It is intermittent, and the efficiency of solar collectors is affected by weather conditions. (Photovoltaic Solar Energy Generation, n.d.)

Geothermal Energy:

Geothermal energy is a renewable energy source that is obtained from the earth's heat. It is abundant and can be harnessed in areas where there are hot springs or geysers. The Stirling engine can be powered by geothermal energy by using the heat from the earth to generate thermal energy. The thermal energy is then used to power the Stirling engine. E. (n.d.)

The use of geothermal energy for powering the Stirling engine has several advantages. It is clean, renewable, and does not produce any emissions or pollution. It is also abundant and can be harnessed in specific areas where there is significant geothermal activity. However, the use of geothermal energy has some limitations. It is location-dependent and is not available in all areas. It is also expensive to set up geothermal plants.

Biomass Energy:

Biomass energy is a renewable energy source that is obtained from organic materials such as wood, crops, and waste products. It is abundant and can be harnessed from various sources. The Stirling engine can be powered by biomass energy by using the organic materials to generate thermal energy. The thermal energy is then used to power the Stirling engine.

The use of biomass energy for powering the Stirling engine has several advantages. It is clean, renewable, and does not produce any emissions or pollution. It is also abundant and can be harnessed from various sources. However, the use of biomass energy has some limitations. (Biomass—a Resource for Environmental Bioremediation and Bioenergy, 2020)

2 STIRLING ENGINE WORKING PRINCIPALS

In its theoretical form, the Stirling cycle is a thermodynamic cycle that includes two phases of constant temperature (iso-therms) and two phases of constant volume (iso-chors). It is considered the most efficient thermodynamic cycle that can be realistically applied in an engine.

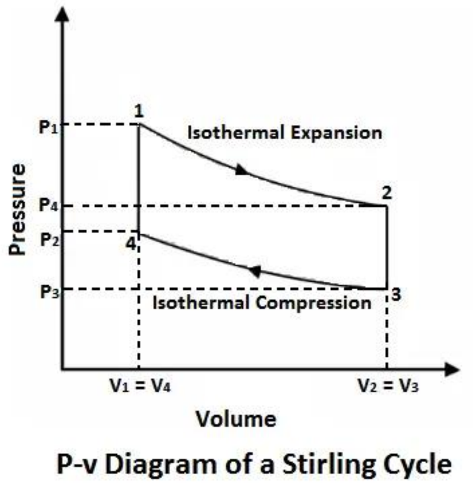

Figure 1 P-V diagram of an idealized Stirling cycle (M, 2019)

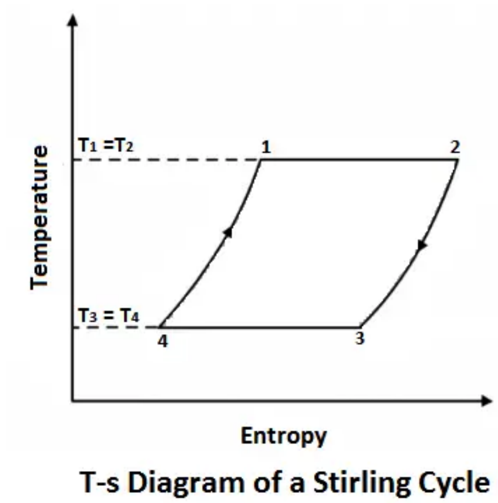

Figure 2 T-s diagram of an idealized Stirling cycle (M, 2019)

The idealized Stirling cycle subjected the working fluid to four thermodynamic processes.

1. Isothermal Expansion
   The gas expands almost isothermally in the expansion space after being heated outside.
2. Iso-choric Heat Extraction
   When gas passes by the regenerator, it is cooled and releases heat to the regenerator, which can be used in the subsequent cycle.
3. Iso-thermal Compression

Since the compression space is cooled between stages, the gas compression process is nearly isothermal.

4. Isochoric Heat-Addition
The regenerator facilitates the transfer of heat to the compressed air, which subsequently flows into the heated expansion section.

2.1 STIRLING CYCLE THERMODYNAMICS

Stirling engines are categorized into three different categories.

1) Alpha Stirling
There are two power pistons in the Alpha Stirling engine that operate independently. One piston operates in a cylinder with a higher temperature located within the heat exchanger. In comparison, the other piston operates in a cylinder with a lower temperature, also located inside the heat exchanger. Despite its high power-to-volume ratio, the engine’s seals encounter technical difficulties due to the hot piston’s high temperature and high durability. (Stirling Engine - Wikipedia, 2021).

The action of the Stirling engine of the alpha type:

The following processes make up the fundamental functioning of an alpha Stirling engine.

i. As a consequence of being heated and expanded, most of the working gas comes into contact with the hot walls of a cylinder and drives the hot piston to the end of its stroke. Additional work is obtained from the hot gas in the cold cylinder, which is 90 degrees out of phase with the hot piston in the cycle.
ii. At this point, the gas volume has reached its maximum. Many of the gas molecules have moved from the hot to the cold cylinder, where they cool and lose pressure, so more gas is moving from the hot to the cold cylinder.
iii. At this stage, most of the gas is still being cooled and is in the cold cylinder. The flywheel (or other pistons on the same shaft) drives the cold piston to compress the remaining gas using its momentum.
iv. After reaching its maximum volume and being heated again, the gas will expand, causing the hot piston to move during its power stroke.

2) Beta-Stirling

The beta Stirling engine uses a conventional shaft to link a power piston and a displacer piston. The main role of the displacer piston is to move the working gas from the hot heat exchanger to the cold heat exchanger without any loss and is purposely designed to have a loose fit, which prevents it from extracting power from the expanding gas. As the operating gas expands, it propels the power piston towards the hot end of the cylinder. The machine's momentum, which a flywheel can enhance, causes the power piston to compress the gas, when pushed in the other way, it will move in the direction of the cylinder's cold end. One advantage of the beta type over the alpha type is that it does not experience the same technical issues with hot-moving seals. (Stirling Engine - Wikipedia, 2021)

Stirling Engine Operation in Beta Type

In a beta Stirling engine, a single cylinder with two pistons is connected to the same crankshaft. The power piston is installed with a tight fit, whereas the displacement piston is assembled with a loose fit.

i. After compressing the gas, the displacer piston was used to move the gas, placing a larger portion of it closer to the hot heat exchanger.
ii. When the temperature of the gas rises, the resulting increase in pressure results in the movement of the power piston towards the end of its stroke.
iii. The displacer piston is moving and altering the gas flow towards the colder end of the cylinder.
iv. At this point, the flywheel begins to rotate and compresses the cooled gas. Since the gas has a lower pressure after cooling, less energy is required for this compression.

3) Gamma-Stirling

In a gamma Stirling engine, the power piston and displacer piston have identical designs but are positioned in different cylinders. The flywheel, however, is still connected to the same flywheel as in a beta Stirling engine. The gas can move between the two cylinders freely without losing its integrity as a unit. While this setup is mechanically more straightforward, it leads to a lower compression ratio, and thus it is often used in Stirling engines with multiple cylinders.

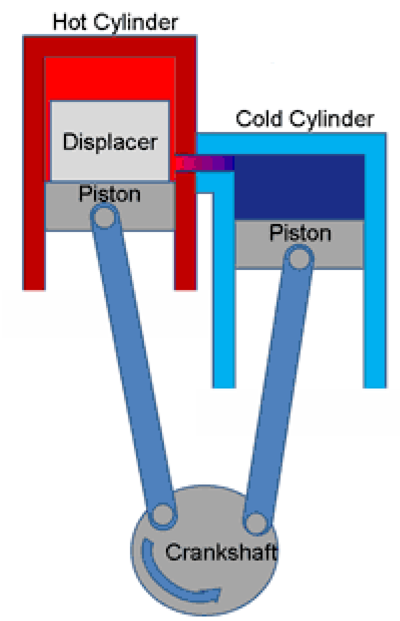

Figure 3 Gamma type Stirling Engine (Gamma Type Stirling Engine - Renewable Energy - Stirling Engine, n.d.)

2.1.1 Difference between the Types

- In the Alpha type of engine, the power piston of several connected cylinders moves the working gas, which is stored at various temperatures.
- The Stirling engines' beta and gamma variants employ only one piston, the displacer, to transfer the working gas between a hot and cold heat exchanger within the same cylinder, removing the requirement for individual cylinders for each heat exchanger.

2.2 THE WORKING FLUID OF THE STIRLING ENGINE

The Fluid Utilized in the Functioning of Stirling Engine is a gas retained in the system between cycles rather than being exchanged. Helium is often the working fluid; however, it can be hydrogen or air. Hydrogen is the best fluid; however, helium, being an inert gas, is frequently used. While the air has poor cycle gas qualities, several designs employ it since it is readily available and inexpensive. The Stirling engine has two spaces: the cold (or compressive) space and the hot (or expansion) space, both of which can be occupied by the cycle gas. Moreover, the gas is compressed and extended alternatively.

2.3 ADVANTAGES AND DISADVANTAGES OF THE STIRLING ENGINE

- These devices can operate using a heat source that is readily accessible.
- Most pollutants may be eliminated by using a continuous combustion method to generate heat.
- Most Stirling engine variants feature their bearings and seals on the colder side of the engine, reducing their reliance on lubricants and enhancing their longevity relative to other reciprocating engine types.
- The engine mechanics are more straightforward than those of other reciprocating engines. No valves are required; therefore, the burner system may be straightforward.
- They need to start more quickly or operate more effectively in cold weather.

DISADVANTAGES OF THE STIRLING ENGINE

- Material needs frequently increase the cost of the engine. A high-temperature heat exchanger often costs 40% more to build and materialize than the entire engine.
- Stirling engines, particularly those operating with slight temperature differences, tend to be heavier concerning the power output they generate.

2.4 RECENT COMMERCIAL DEVELOPMENT

2.4.1 Uses for Combined Heat and Power

In a system that combines heat and power, the waste heat from an engine is utilized to power a secondary heating process while simultaneously generating mechanical or electrical power. Various applications that utilize low-temperature heat can suit this purpose, including industrial processes, home-water heating, and commercial space heating. Furthermore, the engine's power can be harnessed to drive an industrial machine or agricultural activity that produces biomass waste, which can serve as a cost-effective source of fuel for the engine while also reducing waste disposal expenses. When implemented effectively, this entire process can be efficient and economical.

2.4.2 Solar-Power Generation

Positioning a Stirling engine at the focal point of a parabolic mirror allows solar energy to be converted into electricity more efficiently than with non-concentrated photovoltaic cells and similarly to concentrated photovoltaic systems. Southern California Edison (Stirling Engine - Wikipedia, 2021)

reported on August 11, 2005, that they had made a deal to acquire 20,000, over the next two decades, Stirling Energy Systems plans to develop solar-powered Stirling engines. These engines generate 500 megawatts of electricity and will be installed a solar farm covering 4,500 acres. Mirrors will be used to concentrate and direct sunlight onto the engines, generating electricity for power generators.

2.4.3 Heat Pumps

The main difference between a Stirling heat pump and a Stirling cry cooler is that the former typically operates at room temperature. At the same time, the latter has been primarily used for the cost-effective transfer of heat from the outside to the inside of buildings. Although these systems have had limited uptake in commercial settings so far, they are projected to gain broader usage due to the increasing need for energy-efficient solutions and the accelerating adoption of new technologies.

2.4.4 Marine Engines

In the 1980s, Kockums, a shipbuilding company from Sweden, had built at least eight commercially successful submarines powered by Stirling engines. (File: Stirling Cycle.svg - Wikipedia, 2009) By 2005, these submarines had begun to carry compressed oxygen with them.

2.4.5 Nuclear Power

The use of nuclear-powered Stirling engines in power generation facilities has enormous potential. If steam turbines were replaced with Stirling engines, nuclear power plants could become more straightforward and efficient and generate fewer radioactive by-products. Some breeder reactor designs currently use liquid sodium as a coolant, but this can be problematic for a steam plant that requires water or sodium heat exchanger. There are concerns about water reacting violently with sodium; however, incorporating a Stirling engine in the process eliminates the need for water at any cycle stage

2.4.6 Aircraft Engines

Stirling engines could be used if low cost and high-power density can be attained in aircraft engines. They offer numerous benefits such as quieter operation, decreased pollution, higher efficiency at higher altitudes due to lower temperatures, improved reliability due to fewer components and no ignition system, lower vibration, and the capability to utilize safer, less explosive fuels.

3 ALTERNATIVE ENERGY SOURCES

3.1 INTRODUCTION

Energy is an essential concept that plays a crucial role in driving industrial development and promoting economic and social well-being across the globe. It serves as a vital component for continuous human progress and economic growth. Thus, it is crucial to provide everyone with sufficient and affordable access to energy in order to eradicate poverty, improve human well-being, and raise living standards around the globe.

3.2 NEED FOR ALTERNATIVE ENERGY SOURCES

The need for developing alternative fuel sources is increasingly recognized from economic and political standpoints, which is mainly driven by concerns around sustainability related to the environment, economy, and geopolitics. In this regard, renewable energy sources like combustible fuels, solar energy, and other alternatives have been widely viewed as attractive options. According to an IPCC report, The considerable rise in the average temperature worldwide since the mid-1900s can mainly be attributed to the surge in greenhouse gas emissions caused by human activities, leading to a crucial environmental issue. (Alternative Fuel - Wikipedia, 2021)

The combustion of fossil fuels is a significant contributor to greenhouse gas emissions and consequently, to global warming. Additionally, given that the majority of the world's petroleum reserves are situated in the Middle East, there is a general apprehension that a global fuel shortage could fuel unrest and lead to further conflicts in the region.

3.3 ALTERNATIVE ENERGY SOURCES

The definition of alternative fuel is described, " the fuel that contains a minimum of 85% of either ethanol, liquefied natural gas, compressed natural gas, natural gas , hydrogen or liquefied petroleum gas. It can also be a blend of two or more fuels, such as biodiesel, diesel fuel, or kerosene, where at least 20% of the mixture is composed of biodiesel." (Alternative Fuel - Wikipedia, 2021)

Alternative energy sources can be categorized into two main groups:

1. Non-Renewable Energy
   Energy sources that are not replenished or are replenished very slowly are known as non-renewable energy sources.

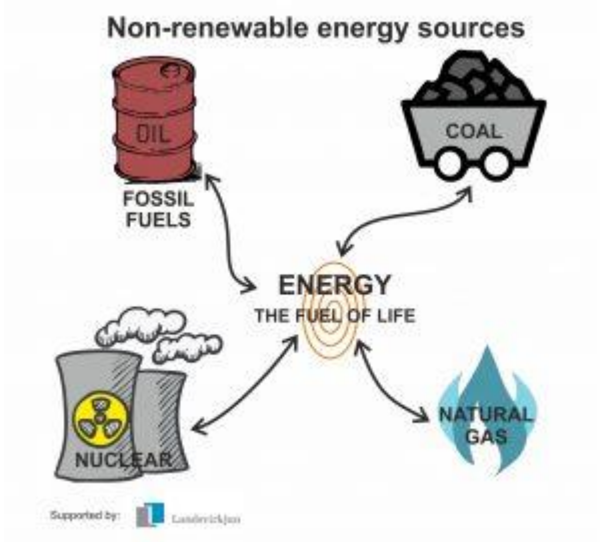

Figure 4 Non Renewable Energies (Non-renewable Energy - Polarpedia, 2019)

I. Nuclear Power

Nuclear power involves using controlled nuclear reactions to extract energy from atomic nuclei. The dominant method used currently is nuclear fission, although other techniques such as nuclear fusion and radioactive decay are also utilized.

II. Natural-Gas

Natural gas is a variety of non-renewable fuel composed primarily of methane with additional hydrocarbons like ethane, propane, butane, and pentane. It also includes several other gases, such as carbon dioxide, nitrogen, helium, and hydrogen sulfide. It is presently the most vital energy source worldwide and is the second most significant fossil fuel. The cost of obtaining natural gas is projected to rise, with Pakistan having already signed a multibillion-dollar contract to import gas via a pipeline from Iran, and another deal with Turkmenistan anticipated to follow. It is predicted that Pakistan's requirement for natural gas will significantly surge in the coming years, with an expected rise of about 50% by 2006.The country plans to switch to domestic gas supplies for future electricity generation projects to reduce reliance on imported oil. Achieving this objective will necessitate a significant increase in natural gas production and imports from neighbouring countries.

III. Liquiefied Petroleum Gas

Propane is a gas with a chemical formula of C3H8 and is classified as one of the liquefied petroleum gases that are typically mixed with natural gas and oil. While it is naturally in a gaseous state, propane can be transformed into a liquid form by either lowering its temperature or increasing its pressure. This liquid form is much more compact than its gaseous state, making it easier to transport and store. When propane is released from a pressurized container via a valve, it returns to its original gaseous form but must be returned to normal pressure before use. As a non-renewable fossil fuel, propane shares characteristics with natural gas and oil. It is colorless and odorless, similar to methane, and is known for being a clean-burning and portable fuel. Consequently, propane is also a popular alternative transportation fuel.

IV. Coal

Coal is a sedimentary rock that can be black or brownish-black and is combustible. It primarily comprises carbon and hydrocarbons, making it a non-renewable energy source formed over millions of years. The energy stored in coal is a product of ancient plants that thrived hundreds of millions of years ago when the earth had swampy forests. Over time, layers of decomposing plants at the bottom of these swamps were gradually buried under water and soil, trapping the plants' energy. The pressure and heat from the upper layers caused the plant matter to transform, ultimately resulting in the formation of coal.

V. Oil

Crude oil, a pungent liquid that ranges in color from yellow to black, is often found in underground reservoirs. It forms as the remains of animals and plants become covered by layers of mud and subjected to high levels of heat and pressure over time. The word "petroleum" refers to this type of oil, also known as "rock oil" or "oil from the earth."

2. Renewable Energy

   When we talk about renewable energy, we mean sources that can be replenished more rapidly than non-renewable ones. This encompasses materials such as wood and other organic substances that can be combusted to generate gaseous or liquid fuels.

I. Biomass

Biomass is a type of organic matter that can be used as a fuel source, comprising living or recently deceased material. While it commonly refers to plants grown for producing biofuel, it can also include animal or plant material used in the production of chemicals, heat, or fibers. Sources of biomass include animals, plants, and their by-products, like garden waste, crop residues, and manure. Because it relies on the carbon cycle, biomass is commonly recognized as a form of renewable energy.

II. Geothermal

Geothermal energy is obtained from the earth's heat and can also be applicable to other celestial bodies. In American English, "geothermal" is commonly used as a noun to refer to geothermal energy or sources or to describe geothermic heat, despite being technically an adjective. The planet initially generated its internal heat through gravitational binding energy during its formation, and it has continuously produced it through the decay of radioactive elements like thorium, uranium, and potassium. Only a mere fraction of the energy received from the Sun is equivalent to the amount of heat that flows from the planet's interior to its surface, specifically 1/20,000.

III. Hydropower

Hydropower, which is also referred to as hydraulic or water power, is a type of energy that is derived from the force or movement of water. This energy can be utilized for practical purposes. Before the widespread availability of commercial electricity, hydropower was commonly used for tasks such as irrigation, as well as to operate different kinds of machinery, including watermills, sawmills, textile machines, cranes used in docks, and elevators designed for personal use.

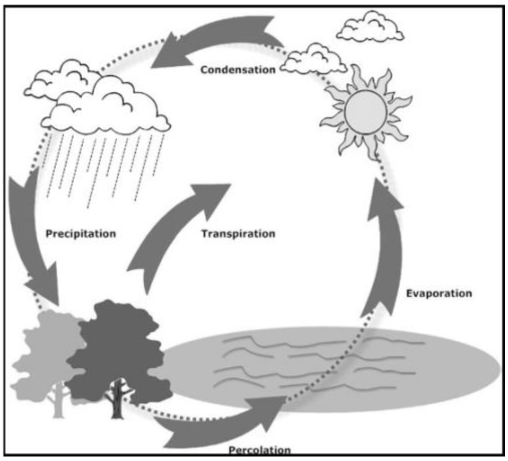

Figure 5 The Hydrological Water cycle (Jabbar & Zainudin, 2020)

IV. Solar Energy

Solar energy is crucial for supporting life on Earth and serves as the main energy source used to fulfill our needs. The sun provides a vast amount of energy that reaches our planet. Interestingly, the energy contained in all the fossil fuels on Earth is equivalent to only 20 days' worth of solar energy. Despite this fact, solar energy accounts for just 1% of the world's energy sources. It's worth noting that solar energy is abundant and freely available, with an infinite supply that doesn't come with any cost. (ScienceDirect.com | Science, Health and Medical Journals, Full Text Articles and Books., n.d.)

4 SOLAR ENERGY

Solar energy has been accessible and cost-free for thousands of years. Studies suggest that the amount of solar energy that reaches the Earth annually is more than 15,000 times the total amount of energy used for commercial purposes worldwide. The sun emits this energy in the form of heat and light, which possesses enormous potential. Consequently, the sun is now considered an alternative energy source.

4.1 Solar Energy Origin

Solar energy originates from thermonuclear reactions occurring within the sun. These reactions entail hydrogen protons and the nuclei of lighter elements, mostly helium, and occur at a temperature of approximately 20 million degrees Celsius. This process results in the conversion of about 4.4 million metric tons of matter into 3.9 million joules of energy per second. (Solar 4 You, n.d.)

4.2 Area with the Highest recipients of Solar Energy

The quantity of solar radiation that reaches the surface of the Earth depends on its latitude. The two dry zones positioned between 15°N and 35°N and 15°S and 35°S receive the largest proportion of solar radiation, with a minimum of 1750 kWh/m² per year. The equatorial region between 15°N and 15°S experiences increased humidity and frequent cloud cover, which limits the solar radiation that reaches the surface. However, the amount of energy received per unit area is second only to that of the arid zone. The regions with the next highest amount of solar energy are located between latitudes 35°S and 45°S, where seasonal effects are more prominent, but the total energy received annually ranges between 1300 and 1750 kWh/m².

Solar energy is less useful in areas located more than 45° away from the equator because the sun's elevation above the horizon is low, and the winter days are short. Consequently, solar energy cannot be used effectively for heating during the months when it is needed the most.

Pakistan has a substantial potential for solar energy, with an average daily insolation rate of approximately 5.3 kWh/m². The southwest region of Pakistan provides ideal conditions for harnessing solar energy, as it receives an insolation rate of 6.0 kWh/m² and enjoys 8 to 8.5 hours of daily sunshine. (Solar 4 You, n.d.)

4.3 Advantages of Using Solar Energy

- The sun is an extremely reliable and inexhaustible source of energy.
- Solar panels are durable energy sources that can be employed in nearly any location for an extended period of time.
- The fluctuations in fuel supply and demand do not influence it, and thus, it is not subject to the continuously rising cost of gasoline.

- By not emitting carbon dioxide, nitrogen oxide, Sulphur dioxide, or mercury into the atmosphere, it keeps our air clean and unpolluted.
- Solar energy systems have the ability to function independently without the need for a connection to power or gas grid. This means that these systems can be installed in remote areas.

4.4 Disadvantages of Using Solar Energy

- One major disadvantage of setting up a solar energy system is the high upfront expense, primarily attributed to the costly semi-conducting materials utilized in their manufacturing.
- Solar energy is currently more expensive than non-renewable electricity provided by utilities. However, due to the increasing frequency of energy shortages, solar energy is becoming more cost-competitive.
- In order to attain an adequate level of efficiency, solar panels need to be installed over a relatively large area.
- Clouds or air pollution affect the generation of solar energy.
- The quantity of sunlight that reaches the surface of the earth is subject to fluctuations and is influenced by a variety of factors, including the location, time of day, season, and current weather conditions.

4.5 Solar Energy Collector

The primary function of a solar collector is to gather solar radiation that comes into contact with its surface. Essentially, it serves as a specialized form of heat exchanger, transforming radiant solar energy into internal energy that can be used to power a transportation medium.

4.5.1 Classification of Solar Energy Collector

Solar collectors can be categorized based on their collection attributes, mounting methodology, and a degree of heating.

On the basis of collecting characteristics solar collector are classified as:

1. Non-Concentrating Collector
2. Concentrating Collector

1. Non Concentrating Collector
   In a non-concentrating solar collector, the surface area responsible for gathering and absorbing solar radiation remains consistent.

   The most prevalent forms of non-concentrating solar collectors include flat plate collectors and evacuated tube collectors.

   a) Flat Plate Collector :

Flat plate collectors do not require a tracking mechanism to capture solar energy and can achieve temperatures of 150 to 200 degrees Fahrenheit. In regions with high temperatures, flat plate collectors are usually a more economical option than evacuated tubes.

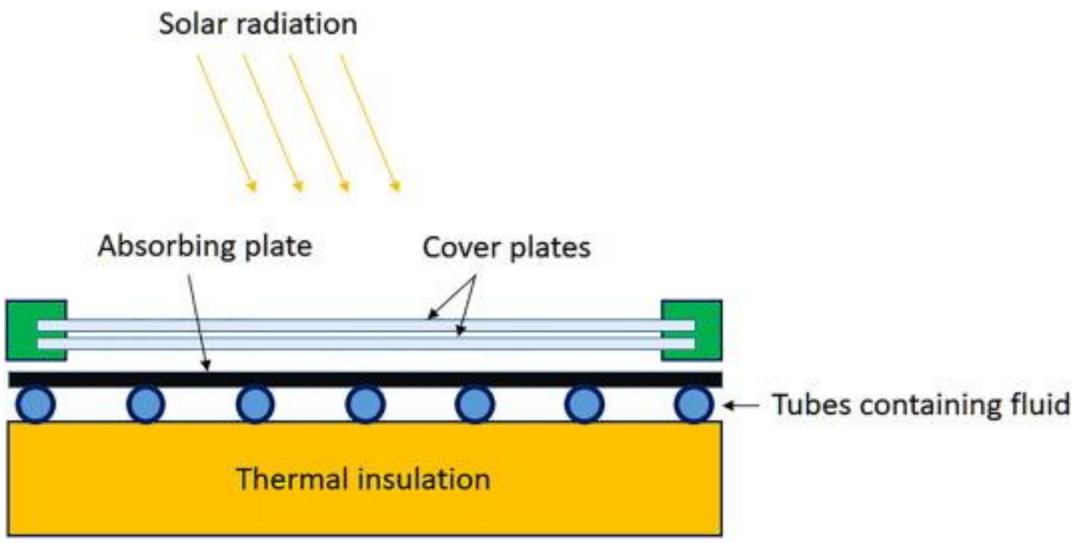

Figure 6 Flat Plate Solar Collector (Dobriyal et al., 2020)

Flat plate collectors come in various designs, but they all have two basic features in common:

• They use a flat plate to capture solar energy.

• A transport medium is employed to extract heat from the plate and transfer it to storage or to the location where it will be utilized.

b) Evacuated Tube Collector:
Modular evacuated tube collectors can be tailored to meet diverse hot water demands. These collectors are composed of rows of transparent glass tubes, with each tube having an absorber tube instead of the absorber plate seen in flat-plate collectors. A light-modulating substance coats the tubes to increase sunlight absorption. As sunlight penetrates the outer glass tube, it heats the absorber tube inside, which can either be made of copper (glass-metal) or coated glass tubing (glass-glass). Typically, glass-metal evacuated tubes are sealed at the manifold end, and the absorber is placed in a vacuum to prevent corrosion problems, even when using dissimilar metals in the absorber and heat pipe. High-end systems have foam insulation in the manifold, and excellent evacuated tubes are generally manufactured using low iron glass.

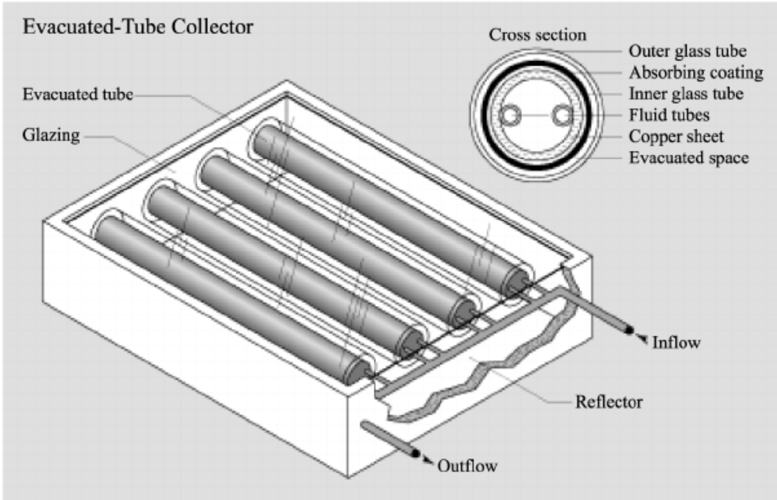

Figure 7 Evacuated or (vacuum) tubes panel (Li, 2010)

- Evacuated tubes can maintain their effectiveness across a broad range of ambient temperatures and heating requirements, based on a specific absorber area.
- With technological advancements, collector panels now have a maximized absorption area, which differs from earlier designs where the absorber area occupied only around 50% of the collector panel.
- When used in groups of 20 to 30 or more, evacuated tube collectors provide a net benefit in winter and a significant advantage in the summer months, despite their high cost. They are especially suitable for very cold ambient temperatures and perform well in conditions with consistently low levels of sunlight.
- Evacuated tube collectors are employed in industrial applications due to their ability to generate high water temperatures or steam.
- Properly designed evacuated tubes can have a lifespan of more than 25 years, which significantly enhances their value.
- An angle of at least 25 degrees is necessary for the installation of heat pipe collectors to allow the fluid inside the pipe to return to the hot absorber. This could be viewed as a disadvantage.

2. Concentrating Collector

   The Concentrating Collector is a technology that makes use of curved reflective surfaces to redirect sunlight onto a smaller receiving area, resulting in a greater radiation flux. This technique is frequently employed in Concentrating Solar Power systems, such as:

- Parabolic Troughs
- Power Towers
- Dish/Engines

a) Parabolic Troughs

A parabolic trough collector consists of a linearly shaped reflective surface that resembles a parabola. The parabolic design of the collector permits it to concentrate the sun's radiation onto a linear receiver placed at the parabola's focal point. To ensure the receiver is consistently in focus, the collector tracks the sun's movement along a single axis from east to west over the course of the day.

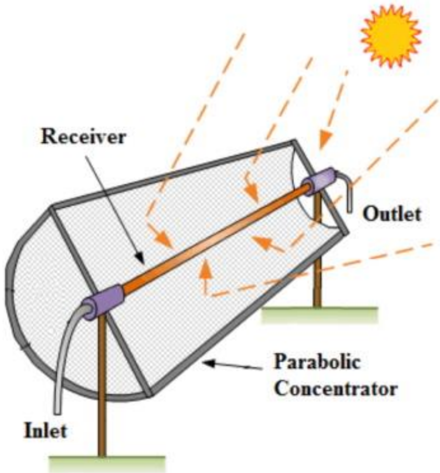

Figure 8 Parabolic Trough (Ghasemi & Ranjbar, 2016)

b) Power Towers

A central receiver, commonly known as a solar power tower, produces electricity by utilizing concentrated solar energy that is directed onto a heat exchanger located on top of a tower. This technology involves the use of flat mirrors, referred to as heliostats, which track the sun's movement and reflect and concentrate its energy onto a central receiver tower. With this method, solar energy can be amplified up to 15,000 times more than the initial amount received. The solar power tower system differs from parabolic troughs in that it doesn't require solar energy to be transported through a medium to a central location. To reduce thermal energy transport losses, only one receiver is utilized in this scenario, which enables direct transfer of solar energy from the heliostats to the receiver through reflection. Power towers need to be significantly large to be economically viable. Although power towers are not as established as parabolic trough technology, they have undergone testing at various facilities worldwide.

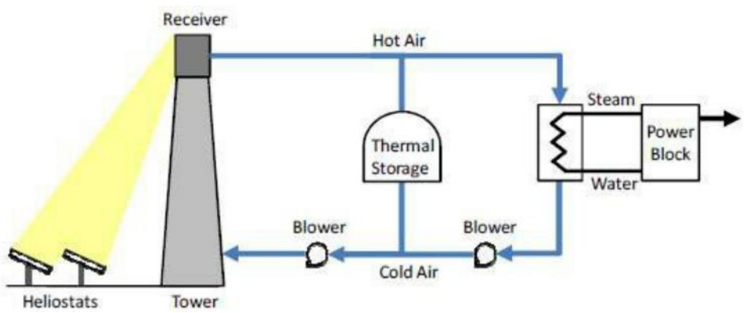

Figure 9 Solar Power Tower (Goel et al., 2014)

c) Parabolic Dish

Concentrating solar collectors are utilized in the solar dish/engine system, which follow the sun on two axes, to focus solar energy at the dish's focal point and keep it directed towards the sun. This technique produces a concentration ratio that surpasses 2,000, resulting in a working fluid temperature exceeding 750°C. The focal point of the dish is large enough to accommodate power generation equipment, making it a viable alternative for remote areas. Moreover, similar to the solar trough, energy gathered from numerous installations can be transmitted to a central location for electricity generation.

In the solar dish/engine system, the engine plays a vital role as it converts heat into mechanical energy by compressing the cold working fluid, heating it, and then expanding it using a turbine or piston to produce work. The engine is connected to an electric generator to convert mechanical power into electrical power.

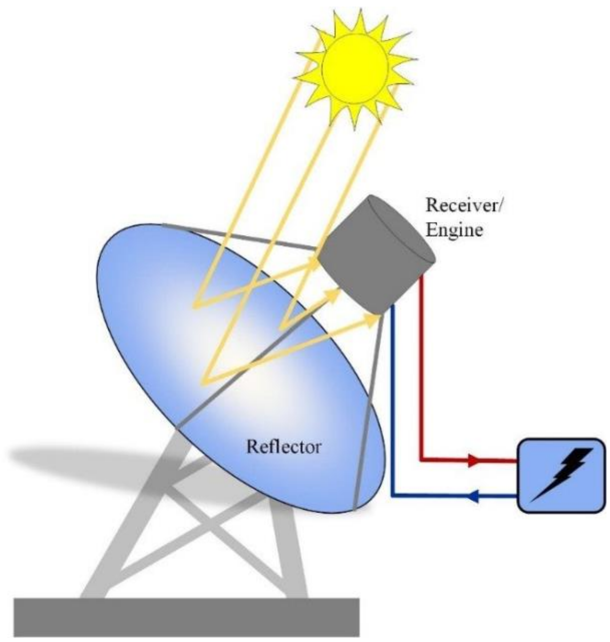

Figure 10 Solar Parabolic Dish (Soomro et al., 2019)

4.5.2 Mounting of Solar collector

There are two possible methods to mount a collector:

- One way to keep the collector in a stable position is to make it adjustable, so the tilt angle can be modified to track changes in solar declination.
- One can enhance the absorption of solar radiation throughout the day by tracking the sun using an equatorial mounting or an azimuth mounting.

4.5.3 Heating Grade

Solar collectors can be classified depending on their capability to deliver the maximum output temperature:

a) Devices that provide low-grade heating, can reach a maximum temperature of 100°C.

b) Devices that provide medium-grade heating, can reach a maximum temperature of 100°-300°C.

c) Devices that provide high-grade heating, can reach with a temperature above 300°C.

4.6 MATERIAL OF A COLLECTOR

The materials commonly used for collector plates include copper, plywood, aluminum, and steel. Copper has the highest thermal conductivity among these materials, but it is also the most costly. Conversely, steel is the least expensive but has the lowest conductivity. The plate's conductivity is critical, especially for water heating collectors. With copper, water tubes bonded to the absorber plate can be spaced further apart than with materials that have lower conductivity. However, if the transfer fluid circulates throughout the entire absorber area, the plate's conductivity becomes less significant. (Solar Thermal Collector - Wikipedia, 2022)

4.7 FLAT-PLATE SOLAR COLLECTORS

Flat plate collectors can collect solar energy without the use of any tracking mechanism. They can directly absorb energy from the sun, as well as from indirect or diffuse radiation that is reflected from the ground, nearby buildings, or clouds. These collectors can achieve temperatures ranging from 150 to 200 degrees Fahrenheit (Solar Thermal Collector - Wikipedia, 2022) and are relatively easy to construct.

The flat plate solar collector can be further classified in two manners.

1. Glazed flat-plate collectors
2. Unglazed flat plate solar collectors

1. Glazed flat-plate collectors

Glazed flat-plate collectors are commonly used and come in two varieties: liquid-based and air-based. They are suitable for applications that require moderate temperatures, typically between 30-70°C.

The flat absorber of these collectors effectively converts sunlight into heat. To minimize heat loss, the absorber is situated between an insulating panel and a glazing material, such as a transparent substance or glass pane. The glazing material is carefully chosen to allow the greatest amount of sunlight to penetrate and reach the absorber.

2. Unglazed Flat plate solar collectors:

To discuss applications that require temperatures below 30C, unglazed flat-plate collectors are considered the most appropriate. These collectors are commonly fabricated using black plastic that has been specially processed to endure exposure to ultraviolet radiation. In contrast to glazed collectors, they do not have a transparent layer, which enables them to absorb more solar energy. Nevertheless, as they lack insulation, a considerable amount of heat may be lost, particularly in colder, windy weather. Such collectors are highly efficient at exchanging heat with the air, meaning that they can even capture heat during hot and windy nights.

4.8 BASIC ASSUMPTIONS AND ANALYSIS FOR FLAT-PLATE SOLAR COLLECTOR

Basic assumptions and analysis for flat-plate solar collector refer to the fundamental principles and calculations employed to create and assess the effectiveness of a specific type of solar thermal collector that uses a flat, rectangular surface to absorb and convert sunlight into heat energy. These assumptions and analysis typically involve considerations such as solar radiation, collector geometry, heat transfer mechanisms, and system efficiency, which are used to determine factors such as the collector's heat output, thermal efficiency, and potential energy savings.

a. Assumptions

The underlying presumptions in the steady-state thermal analysis are as follows:

1. Thermo-physical properties remain uniform and constant with temperature throughout the collector area.
2. Heat transfer and fluid flow are linear.
3. The analysis is based on May data.
4.

b. Analysis

The power output of a Stirling engine that runs on solar energy was determined by computing the heat transfer rate and the temperature of the outlet fluid.

For notification and specifications (See Appendix 1)

4.9 Calculations

a) Solar Angles

The basic solar angles required to calculate the amount of solar irradiation incident at a particular area are solar azimuth, solar attitude, and declination angle.

b) Solar Altitude (β)
Solar altitude is the vertical angle on a horizontal plane between the sun's rays and the surface of the earth (See Appendix 2).

c) Solar Azimuth(ϕ)
Solar azimuth is the horizontal angle between the line of sight to the south and the sun's rays projected on the ground. This angle is calculated by determining the angle between the observer's line of sight to the sun and the line of sight to the south (See Appendix 2).

d) Solar Declination
Solar declination is the angle between the Earth's equator plane and the line that joins the Earth and the sun. This angle varies throughout the year.

Table 1 Monthly Averaged Declination for Karachi (Baquero, n.d.)

Lat 24.54 Lon 67.08	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Average	-20.7	-12.3	-1.79	9.71	18.8	23.0	21.2	13.7	3.08	-8.46	-18.1	-22.8

e) Angle of Incidence (θ)
The angle of incidence is the angle between the surface's normal and the direction of the sun's rays that hit the surface (See Appendix 2).

f) Solar Irradiation

It is defined as:

" The quantity of electromagnetic radiation that reaches the Earth's surface" (Solar Radiation, n.d.)

The amount of radiation, both direct and diffuse, that can be received at any given location, also termed as isolation (Incident Solar Radiation).

$I= (I_D * \cos\theta) + I_d$ (Kittipuckdee, n.d.) ……………………..(4.1)

g) Direct radiation on horizontal surface (I_D)
The amount of solar radiation that reaches the Earth's surface, including both direct and indirect radiation from the Sun. Any direct radiation is prevented by a shadow band or tracking disk.

Table 2 Monthly Averaged Insolation Incident on a Horizontal Surface for Karachi (Baquero, n.d.)

Lat 24.54	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec

Lon 67.08												
22-year Average	4.38	5.18	5.93	6.65	6.67	5.44	5.27	5.62	5.24	4.50	4.11	5.44

I_D=6.67 kWh/m²_day

h) Diffuse normal radiation (I_d)

This pertains to the amount of solar radiation that reaches a level surface at the Earth's surface, perpendicular to the direction of the sun's rays, with the exclusion of the ambient sky radiation.

I_d=2.13 kWh/m²_day (Baquero, n.d.)

i) Daylight Hours

It is the time between sunrise and sunset.

Table 3 Monthly Averaged Daylight Hours for Karachi (Baquero, n.d.)

Lat 24.54 Lon 67.08	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Average	10.8	11.3	12.0	12.7	13.3	13.6	13.5	12.9	12.3	11.6	10.9	10.6

Day light hours = 13.3 hours

j) Insolation in terms of kW/m²

See (Appendix 2).

4.10 Energhy Balance

One can utilize an energy balance to determine the thermal efficiency of a solar thermal collector. This calculation involves determining the percentage of incoming radiation that converts into useful energy for the working fluid. The collector's absorber plate is responsible for absorbing a specific amount of energy, which is considered the useful energy gained by the collector.

$q'' = 1\,\tau\alpha - [\{\sigma (T_a^* - T_c^*)\} / R_{rad}] - [\{(T_a - T_c)\} / R_{conv}] - [\{(T_a - T_\infty)\} / R_{cond}]$ (Kittipuckdee, n.d.) ……………..(4.2)

For further calculations (See Appendix 3).

Table 4 Flat Plate Analysis

Area of Base Plate (m^2)	q_{conv} in tubes (W)	T_o (K)	q (with 35% losses) (W)	Carnot Efficiency of the Engine η_c (%)	Stirling Efficiency of the Engine Hs (%)	Power outup of the Engine (W)
3.5	262.57	313.93	170.67	3.48	1.74	2.97
7	525.28	334.88	341.62	9.52	4.76	16.26
10	750.2	352.82	487.63	14.121	7.060	34.43

4.10.1Compression ratio of stirling engine driven by flat plate

The thermal efficiency of an engine can be expressed using the following equation:

η= [R* (T_3-T_1) *lnr] / [R*T_3 * lnr + {(1-ε)* C_v *(T_3 − T_1)}] ((PDF) Stirling Engines - G Walker (Oxford, 1980) WW - DOKUMEN.TIPS, n.d.)

For Calculated Compression ratio (See Appendix 3) .

4.11 Parabolic Trough

4.11.1 Introduction

The parabolic trough solar collector is a type of solar collector that employs a reflector with a linear parabolic shape to concentrate the sun's energy onto a linear receiver, positioned at the focal point of the parabolic shape. To maintain focus, the collector follows the sun on a single axis, tracking its movement from east to west throughout the day. The parabolic shape of the collector permits it to amplify the sun's radiation to a concentration ratio that ranges between 30 to 100 times its normal intensity on the receiver pipe, located along the focal line. As a result, the collector can achieve operational temperatures above 400 degrees Celsius. A collection field typically consists of a significant number of single-axis tracking parabolic trough collectors.

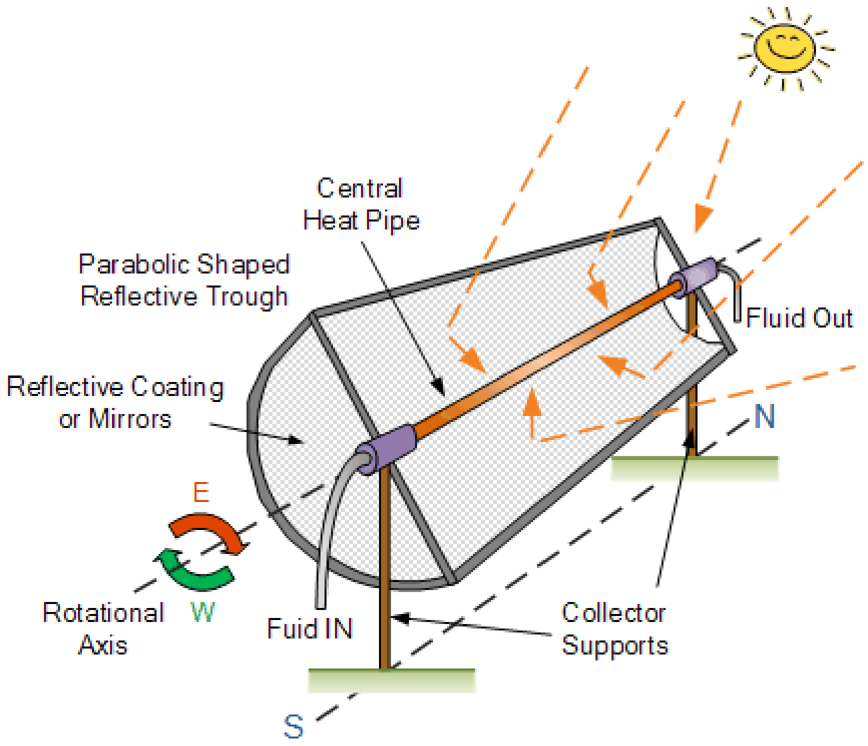

Figure 11 Parabolic Trough Solar Collector (Parabolic Trough Reflector for Solar Thermal System, 2022)

4.11.2 Principle of Operation

To concentrate solar energy onto a linear receiver, the design of a parabolic trough utilizes the principle of geometry that reflects parallel rays of light to the focal point of a parabola. The linear receiver is a pipe containing a liquid that absorbs heat transferred through the pipe wall and conveys it to the thermal load. The process of using a parabolic trough involves gathering solar radiation across a broad surface and directing it towards a smaller receiver. This results in a concentration ratio of 30-80 times the intensity of the sun, allowing for the creation of thermal energy at high temperatures.However, to achieve this concentration, the trough must accurately track the sun's movement along a single axis throughout the day. This requires a tracking system that maintains the alignment of the trough within a small fraction of a degree.

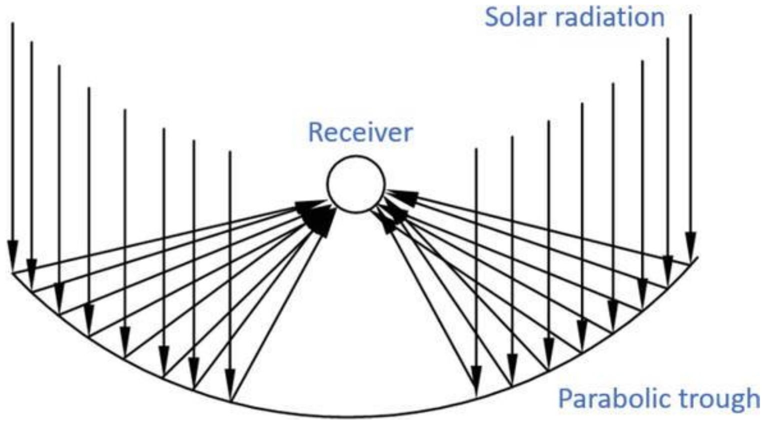

Figure 12 Insolation over Parabolic Trough Solar Collector (Phu & Tu, 2021)

In trough concentrators, the receiver comprises a metal absorber surrounded by a glass tube. The absorber is coated with a selective surface to optimize absorption of visible light and minimize radiative loss in the infrared range. The glass tube provides insulation, shields against wind, and reduces conductive and convective heat loss. The distance between the absorber tube and the inner surface of the glass is optimized to minimize heat loss due to air gap. Furthermore, the glass acts as a barrier against infrared radiation, which further reduces heat loss. An anti-reflective coating is applied to the glass tube to reduce optical losses caused by reflection, as some light from the parabolic reflector is reflected off the inner and outer surfaces of the glass and absorbed by the glass.

4.11.3 Advantages

- The temperatures achieved are extremely high. Such high temperatures are ideal for producing electricity through conventional means such as steam turbines or direct high-temperature chemical reactions.
- The system has a high level of efficiency. By focusing sunlight, the current system is capable of achieving greater efficiency compared to basic solar cells.
- Using affordable mirrors allows for a larger surface area to be covered, as opposed to using costly solar cells.
- The optical fiber cable can be used to redirect concentrated light to a desired location.
- The parabolic trough is utilized in numerous solar power plants due to its simple fabrication and tracking equipment, which is less complicated than that of the dish. Hot oil flows through the flow tube at the center of the parabolic trough.

4.11.4 Disadvantages

- To ensure that sunlight remains focused on the collector, concentrating systems require dual-axis sun tracking.
- Concentrated solar systems are not efficient at producing electricity in situations where light is dispersed. While solar cells can still generate some power in mildly cloudy conditions,

concentrating systems experience a notable reduction in their output during cloudy periods due to the fact that diffused light cannot be actively concentrated.

4.12 BASIC ASSUMPTIONS AND ANALYSIS FOR PARABOLIC TROUGH SOLAR COLLECTOR

4.12.1 Assumptions

The basic assumptions that are used in the steady state thermal analysis are listed as follows:

1) Steady state conditions.

2) Uniform heat flux at inner surface.

3) Adiabatic outer surface.

4) Fully developed flow at exit.

5) Thermo physical properties are constant.

6) Heat transfer and fluid flow are one dimensional.

7) Parabolic trough is of stationary type.

8) Incident solar radiation on parabolic trough is completely focused at tube without any losses to the atmosphere.

9) Calculations have been performed by taking the data of the month of May.

4.12.2 Analysis

For notifications, specifications and calculations (See Appendix 4).

Table 5 Parabolic Trough Analysis

T_{w2} (°C)	T_{w1} (°C)	T_o (°C)	q (with 35% losses) (W)	Carnot Efficiency of the Engine η_c (%)	Stirling Efficiency of the Engine ηs (%)	Power outup of the Engine (W)
80	92.16	67.063	418.6	10.9	5.44	22.77
100	128.6	90.85	418.6	16.7	8.36	35
150	219.84	150.366	418.6	28.4	14.2	59.5

a) Compression ratio of Stirling engine of parabolic trough

Thermal efficiency of an engine is given by the following relation

$\eta = [R^* (T_3 - T_1) * \ln r] / [R^* T_3 * \ln r + \{(1-\varepsilon) * C_v * (T_3 - T_1)\}]$ ((PDF) Stirling Engines - G Walker (Oxford, 1980) WW - DOKUMEN.TIPS, n.d.)

For calculated compression ratio (See Appendix 4).

5 COMUSTIBLE FUELS

5.1 Introduction

Fuels that are combustible are obtained from the remains of organic material from plants and animals that existed millions of years ago.These remains underwent a natural process of sedimentation and were subjected to high pressure and temperatures for millions of years, resulting in the formation of liquid hydrocarbons, which we commonly call crude oil. The task of separating these hydrocarbons into different products, such as gasoline, diesel, heating oil, jet fuel, and others, is carried out by refineries.

5.2 Combustion

The process of combustion involves a series of chemical reactions between a fuel and an oxidizing agent, resulting in the release of heat, and sometimes light.

Fuel + Oxygen -→ Heat + Water + Carbon dioxide

First law of thermodynamics stated that:

"Energy can neither be created nor be destroyed"

The enery balance for a chemically reacting steady-flow system:

$Q_{in} + W_{in} + \Sigma N_r * *\{h_f^0+(h-h^0)\}_r = Q_{out} + W_{out} + \Sigma N_p*\{h_f^0+(h-h^0)\}_p$

The combustion process associated with heat supply (heat output) but no work component.

When dealing with a continuous combustion process, the energy balance equation is expressed as follows:

$Q_{out} = \Sigma N_p*\{h_f^0+(h-h^0)\}_p - \Sigma N_r * *\{h_f^0+(h-h^0)\}_r$ ....(5.1)

The process of burning fossil fuels in the presence of air is influenced by several factors that affect the combustion temperature. These factors consist of the heat content of the fuel, the optimal ratio of air to fuel (A/F), the thermal capacities of both the fuel and air, as well as the temperatures of the incoming air and fuel.

5.2.1 Adiabatic Flame Temperature

It is defined as;

"**Highest possible temperature that can be achieved during combustion"**

Characteristics of adiabatic flame temperature:

- Adiabatic Flame Temperature never achieved in practice.
- No realistic combustion chamber is adiabatic.
- Dissociation lowers temperature.

Raising the temperature of the air and fuel input, as well as approaching a stoichiometric air ratio of one, results in an increase in the temperature of an adiabatic flame.

Types of adiabatic flame temperature:

The adiabatic flame temperature can be classified into two types based on the method of completion.

- The adiabatic flame temperature at constant volume is the temperature attained in a combustion process where no work, heat transfer, kinetic or potential energy changes occur.
- The constant pressure adiabatic flame temperature is attained in a combustion process without any changes in kinetic or potential energy, or heat transfer, but unlike the constant volume process, some energy is used to modify the system's volume. Consequently, the constant pressure temperature is often lower.

Analysis of adiabatic flame temperature:

The adiabatic flame temperature can be calculated in three ways:

1. Using an average value of Cp
2. Using the tabulated evolution of Cp with temperature
3. Using the tabulated values for gad enthalpy

Analaysis of AFT using the tabulated values for gas enthalpy:

Adiabatic process is one in which there is no heat transfer. Eq (4.1) becomes

$$0 = \Sigma N_p * \{h_f^0 + (h - h^0)\}_p - \Sigma N_r * *\{h_f^0 + (h - h^0)\}_r$$

$$\Sigma N_p * \{h_f^0 + (h - h^0)\}_p = \Sigma N_r * *\{h_f^0 + (h - h^0)\}_r \quad \text{..........................(5.2)}$$

$$H_{Product} = H_{Reactant} \quad \text{..........................(5.3)}$$

5.3 Compressed Natural Gas

Comprised mainly of methane, natural gas is a fuel that also includes ethane, propane, butane, and pentane, as well as carbon dioxide, nitrogen, helium, and hydrogen sulfide. As the world's second-largest fossil fuel, natural gas plays a crucial role in the global energy supply. There is a predicted increase in investment for gas procurement. In the United States, there has been a significant surge in the use of natural gas, especially since the discovery of vast shale gas reserves. Furthermore, natural gas finds application in the production of various products, including chemicals and fertilizers.

Compared to other fossil fuels, natural gas has a relatively lower carbon footprint, which is one of its significant advantages. It emits fewer greenhouse gases when burned, making it a cleaner option for power generation than coal or oil. Additionally, natural gas is a versatile fuel that finds application in several areas, including powering vehicles, heating buildings and homes, and generating electricity.

Despite its many benefits, the extraction and transport of natural gas can have negative environmental impacts. For example, the drilling process for shale gas can cause water pollution and contribute to climate change if methane leaks occur during production and transportation.

Despite these concerns, the demand for natural gas is expected to continue to grow in the coming years, particularly in developing countries where energy demand is rising rapidly. As such, the investment associated with gas procurement is projected to increase, as countries seek to secure their energy supplies and reduce their carbon footprint through the use of cleaner-burning fuels like natural gas.

Table 6 Chemical Composition of Compressed Natural Gas

Component	Typical wt.%
Methane (CH_4)	70-90
Ethane (C_2H_6)	5-15
Propane(C_3H_8) and Butane (C_4H_{10})	<5
CO_2,N_2,H_2S,etc	Balance

Advantages:

Due to its light weight, natural gas is less dense than air. Additionally, it has very limited flammability ranges. As a result, if a leak occurs, there is a high probability that the fuel will disperse safely into the atmosphere, without causing any ignition hazards..

Adiabatic Flame Temperature of CNG:

The basic combustion equation for compressed natural gas has been shown below.

$CH_4 + 2(O_2 + 3.76N_2) \dashrightarrow CO_2 + 2H_20 + 7.52N_2$

(See Appendix 5)

Table 7 Enthalpy of formation and standard enthalpy at reference site

Constituents	h_f^0 (kJ/kmol)	h^0 (kJ/kmol) (at 298K)
CH_4	-74850	-
O_2	0	8682

N_2	0	8669
CO_2	-393520	9364
H_2O	-241820	9904

In order to find out the values of h_{CO2}, h_{H2O} and h_{NO2}, assuming different temperatures to satisfies the eq 3 (See Appendix 6).

Table 8 Sensible Enthalpy at Different Temperature

Temperature(K)	hCO2 (kJ/kmol)	h_{H2O} (kJ/kmol)	h_{N2} (kJ/kmol)	L.H.S of eq(4.6)	R.H.S of eq (4.6)
2400	125152	103508	79320	928654.4	896673
2000	100804	82593	64810	753361.2	896673
2300	119035	98199	75676	884516.52	896673
2350	122091	100846	77496	906552.92	896673
2325	120563	99522.5	76586	895534.12	896673
2330	120868.6	99787.2	76768	897738.36	896673
2329	120807.48	99734.26	76731.6	897297.63	896673
2328	120746.36	99479.72	76695.2	896452.64	896673

By interpolating between different temperature ranges, the adiabatic flame temperature for CNG thus obtained is 2328 K.

Heat Energy Evolved From Stirling Engine using CNG as an Energy Source:

The relationship that governs the quantity of thermal energy produced during a combustion process is expressed in (See Appendix 5).

Theoretical Efficiency of Stirling Engine Usng CNG as an Energy Source:

Stirling engine is one that approaches to Carnot engine to a large extent.

(See Appendix 5) how theoretical efficiency is determined.

Power Output of Stirling Engine Using CNG as an Energy Source:

Efficiency of an engine is the ratio of powr output to the amount of heat supplied to it (See Appendix 5).

Compression Ratio of Stirling Engine Using CNG as an Energy Source:

Thermal efficiency of Stirling engine is given by the following relation:

η= [R* (T_3-T_1) *lnr] / [R*T_3 * lnr + {(1-ε)* C_v *(T_3 − T_1)}] ((PDF) Stirling Engines - G Walker (Oxford, 1980) WW - DOKUMEN.TIPS, n.d.)

For further calculations (See Appendix 5).

5.4 Liquified Petroleum Gas

Liquefied Petroleum Gas (LPG) is a fossil fuel that exists in a gaseous state but can be converted to liquid form through moderate pressure. LPG is produced from refining natural gas and oil, and is composed of various hydrocarbon blends. The LPG used as fuel for vehicles is a liquid mixture consisting of at least 90% propane, 2.5% butane and higher hydrocarbons, with ethane and propylene making up the rest.

Table 9 Chemical compistion of Liquefied Natural Gas

Component	Typical wt.%
Methane (CH_4)	90
Ethane (C_2H_6)	6
Propane(C_3H_8) and Butane (C_4H_{10})	<5
CO_2,N_2,H_2S,etc	Balance

Advantages:

- LPG does not pollute environment as much as compare to other alternatives such as gasoline diesel and CNG.
- Gasoline emits more carbon than LPG due to its lower octane rating. LPG's higher octane rating results in less carbon buildup and therefore, LPG emits up to 40 percent fewer carbon dioxide emissions compared to gasoline.

Disadvantages:

- Starting an engine that runs on propane could be challenging in cold weather, where temperatures are below 32 degrees Fahrenheit, because the vapor pressure of propane is low at low temperatures.
- A gallon of LPG contains less energy compared to a gallon of gasoline.
- Compared to gasoline and CNG, LPG is usually a costlier fuel option.

Adiabatic Flame Temperature of LPG:

The basic combustion equation for liquified petroleum gas has been shown below.

$C_2H_8 + 5(O_2+3.76N_2) \rightarrow 3CO_2 + 4H_2O+18.8N_2$

(See Appendix 6)

Table 10 Enthalpy of formation and standard enthalpy at reference state

Constituents	h_f^0 (kJ/kmol)	h^0 (kJ/kmol) (at 298K)
CH_4	-103628	-
O_2	0	8682
N_2	0	8669
CO_2	-393520	9364
H_2O	-241820	9904

In order to find the out the values of h_{CO2}, h_{H2O} and h_{NO2}, assuming different temperatures to satisfies the eq 5 (See Appendix 6).

Table 11 Sensible Enthalpy at Different Temperature

Temperature(K)	hCO2 (kJ/kmol)	h_{H2O} (kJ/kmol)	h_{N2} (kJ/kmol)	L.H.S of eq(4.9)	R.H.S of eq (4.9)
2600	137449	114273	86650	2498459	2274897.2
2400	125152	103508	79320	2280704	2274897.2
2394	124784.68	103188.56	79101.12	2274210.84	2274897.2

Heat Energy Evolved From Stirling Engine using LPG as an Energy Source:

The amount of heat energy released as a result of combustion process is determined by the relation; (See Appendix 6).

Efficiency of Stirling Engine Using LPG as an Energy Source:

Stirling engine is ome that approaches to Carnot engine to a large extent.

The theoretical efficiency of an engine is determined by (See Appendix 6).

Power Output of Stirling Engine Using LPG as an Energy Source:

Efficiency of an engine is the ratio of power output to the amount of heat supplied to it.(See Appendix 6)

Compression Ratio of Stirling Engine Using LPG as an Energy Source:

The thermal efficiency of a Stirling engine is expressed by the following equation:

$$\eta = [R * (T_3 - T_1) * \ln r] / [R * T_3 * \ln r + \{(1-\varepsilon) * C_v * (T_3 - T_1)\}]$$

(See Appendix 6)

5.5 Gasoline

Gasoline comprises more than 500 hydrocarbons, consisting of carbon atoms ranging from 5 to 12. It is typically produced by fractionally distilling crude oil, separating the oil into several fractions based on the boiling points of hydrocarbons with different chain lengths. This method yields approximately 25% straight-run gasoline per barrel of crude oil.

Advantages:

- Gasoline has the benefit of being a naturally occurring product of petroleum and is produced through a distillation process that does not generate dense smoke similar to diesel fuel..
- Its liquid form is particularly advantageous as it enables easy handling and transportation, in contrast to compressed gaseous fuels.
- None of the alternatives (listed below) delivers as much energy content as gasoline.

Disadvantages:

- The disadvantage of gasoline is that it needs high technology to separate from crude oil and costly fuel systems.
- Unlike gaseous fuels like compressed natural gas (CNG) or liquid propane (LP), the exhaust produced by gasoline engines can be breathed in, except in cases where there is oxygen depletion.
- Because the emissions produced by the burning of gasoline it is major source of air pollution.

Table 12 Chemical composition of Gasoline

Component	Typical wt.%
Methane (CH_4)	90
Ethane (C_2H_6)	6
Propane(C_3H_8) and Butane (C_4H_{10})	<5
CO_2,N_2,H_2S,etc	Balance

Adiabatic Flame Temperature of Gasoline:

The basic combustion equation for gasoline has been shown below.

$C_8H_{18} + 12.5(O_2+3.76N_2) \rightarrow 8CO_2 + 9H_2O+47N_2$

For further calculations (See Appendix 7)

Table 13 Enthalpy of formation and standard enthalpy at reference state

Constituents	h_f^0 (kJ/kmol)	h^0 (kJ/kmol) (at 298K)
CH_4	-208500	-
O_2	0	8682
N_2	0	8669
CO_2	-393520	9364
H_2O	-241820	9904

In order to find the out the values of h_{CO2}, h_{H2O} and h_{NO2}, assuming different temperatures to satisfies the eq 5 (See appendix 6).

Table 14 Sensible Enthalpy at Different Temperature

Temperature(K)	hCO2 (kJ/kmol)	h_{H2O} (kJ/kmol)	h_{N2} (kJ/kmol)	L.H.S of eq(4.6)	R.H.S of eq (4.6)
2600	137449	114273	86650	6200599	5687531
2400	125152	103508	79320	5660828	5687531

2408.89	125697.3	103983.62	79645.196	5684755.23	5687531
2409.9	125759	104037.11	79681.77	5687446.42	5687531

Heat Energy Evolved From Stirling Engine using Gasoline as an Energy Source:

The amount of heat energy released during a combustion process is determined by a formula .(See Appendix 7)

Efficiency of Stirling Engine Using Gasoline as an Energy Source:

Stirling engine is ome that approaches to Carnot engine to a large extent.

The theoretical efficiency of an engine is determined .(See Appendix 7)

Power Output of Stirling Engine Using LPG as an Energy Source:

Efficiency of an engine is the ratio of powr output to the amount of heat supplied to it.(See Appendix 7)

Compression Ratio of Stirling Engine Using LPG as an Energy Source:

Thermal efficiency of Stirling engine is given by the following relation:

$$\eta = [R^* (T_3 - T_1) ^*\ln r] / [R^*T_3 ^* \ln r + \{(1-\varepsilon)^* C_v ^*(T_3 - T_1)\}]$$

For Calculated Compression ratio (See Appendix 7).

6 CONCLUSION

The power output of the Stirling engine varies depending on the energy source used. For flat plate solar collectors, the output is 34.43 W, while parabolic trough solar collectors produce 59.50 W. The output is significantly higher for combustible fuels, such as compressed natural gas (19.8 kW), liquefied petroleum gas (20.5 kW), and gasoline (19.9 kW).

The compression ratio of the Stirling engine also differs based on the energy source. Flat plate solar collectors have a ratio of 1.05, parabolic trough solar collectors have a ratio of 1.08, compressed natural gas has a ratio of 1.4, liquefied petroleum gas has a ratio of 1.45, and gasoline has a ratio of 1.3.

After evaluating the power output of the Stirling engine from different sources, it can be concluded that combustible fuels are the best possible alternative energy sources.

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APPENDIX 1: NOTATIONS AND SPECIFICATIONS

NOTATIONS

Hour angle = H

Latitude = L_a

Longitude = L_o

Declination angle = δ

Solar altitude = β

Solar azimuth =ϕ

Angle of incidence = θ

Direct radiation from sun = I_D

Diffuse radiation component from sky = Id

Total Solar Irradiation of surface = I

Transmittance of cover plate = τ

Absorptivity of base plate = α

Absorber plate temperature = T_a

Glass cover plate temperature = T_c

Ambient temperature = T∞

Conductive Resistance = Rcond

Convective Resistance = Rconv

Radiative Resistance = Rrad

Conductive coefficient = k

Stefan Boltzman Constant = σ

Grashhof no =Gr

Volumetric thermal expansion = β

Spacing between glass cover and base plate = L

Kinematics viscosity = v

Emissivity of cover plate = ϵ_c

Emissivity of absorber plate = ϵ_a

Convective Coefficient = h_i

Nusselt No= Nu

Heat Flux=q"

Heat Rate = q

Carnot Efficiency of the Engine = η_c

Stirling Efficiency of the Engine = η_s

SPECIFICATIONS

Transmittance of cover plate = τ = 0.9

Absorptivity of base plate = α= 0.92

Absorber plate temperature = T_a= 353 K (80° C)

Glass cover plate temperature = T_c= 313 K (40° C)

Ambient temperature = T_∞= 305 K (32° C)

Length of base plate L_b= 2.25m

Width of plate = W = 1.5m

Area of plate =A=L_b * W

A = 2.25 * 1.5

Area of plate = A = 3.4 m^2

No of tubes = 10

Spacing between tubes = 0.05m

Diameter of tubes = d = 0.05m

Inlet temperature of fluid in tubes = T_{in}= 293K

Outlet temperature of fluid in tubes = T_{out}= unknown

Stefan Boltzman Constant = σ = 5.67 e -8

Emissivity of cover plate = ϵ_c= 0.95

Emissivity of absorber plate = ϵ_a = 0.92

APPENDIX 2: CALCULATIONS

SOLAR ALTITUDE

$\sin\beta = [(\cos L \cos H * \cos\delta) + (\sin L * \sin\delta)]$[?]

$\sin\beta = [\{\cos(24.9°) * \cos(150) * \cos(18.8°)\} + \{(\sin(24.9°) * \sin(18.8°)\}]$

$\beta = \sin^{-1}(0.9647)$

$\beta = 74.73°$

SOLAR AZIMUTH(Φ)

$\sin\phi = \{(\cos\delta * \sin H)/(\cos\beta)\}$[?]

$\sin\phi = [\{\cos(18.8°) * \sin(15°)\} / \{\cos(74.73°)]$

$\phi = \sin^{-1}(0.9303)$

$\phi = 68.48$

Angle of Incidence (θ)

$\theta = 90° - \beta$

$\theta = 90° - 74.73°$

$\theta = 15.27°$

INSOLATION IN TERMS OF KW/M²

$I_D = 6.67/13.3\ kW/m^2$

$I_D = 501.504\ W/m^2$

$I_d = 2.13/13.3\ kW/m^2$

$I_d = 160.15\ W/m^2$

eq (4.1) implies

$I = \{(501.504) * \cos(15.27°)\} + 160.15$

$I = 644\ W/m^2$

APPENDEIX 3: ENERGY BALANCE

ENERGY BALANCE

- Rrad= (1/ Єc) +(1/Єa) -1 (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

R_{rad} (1/0.95) +(1/0.92) - 1

R_{rad}=1.139 m² K/W

- $R_{conv}=1/h_i$ (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

Since there is a free convection between glass cover and absorber plate, in order to find out convective heat transfer coefficient, we have to determined grashhof no.

$G= (g.\beta (T_a-T_c) L^3)/v^2$

$\beta=1/T$

$\beta=1/333$

$\beta=0.003$

G_r= [{(9.8* 0.003* (353-313) * 0.053)} / $(0.194e-4)^2$] (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

G_r= 3.90 e 5

$N_u=0.152*(G_r)^{0.281}$

N_u=0.152* $(3.90 \text{ e } 5)^{0.281}$

N_u=5.67

- Since Nu- (h_i* L)/k (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

Where k = 0.02750 W/m -K for air at 333 K

This implies that;

h_i = (5.67 0.02750)/0.05

h_i = 3.12 W/m-K

R_{conv} =1/h_i

R_{conv} =1/3.12

R_{conv} = 0.321 m² K/W

- R_{cond} = La/k (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

Where k is 0.040 for rock wool insulation (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

R_{cond} =0.05/0.040

R_{cond} =1.25 m² K/W

Now eq (4.2) becomes

q"= = (644^ * 0.9*0.92) - [{5.67e - 8($353^4 - 313^4$)} / 1.139] - [{(353 - 313)} / 0.321] -

[{(353 - 305)} / 1.25]

q"=75.02 W/m²

Under steady state conditions:

$q''_{cond\ by\ absorber\ plate} = q''_{conv\ in\ tubes}$ (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

As we know that

$q''_{cond\ by\ absorber\ plate}$=75.02 W/$m^2$

$q''_{conv\ in\ tubes}$=75.02 W/m^2

Heat Flux refers to the quantity of heat transferred from a surface that is perpendicular to the direction of the flow.

- q"=q/A

  $q_{cond\ in\ tubes} = q''_{conv\ in\ tubes}$*A

  Convective heat rate for internal flow can also be determined from the relation.

- q=m* C_p* (T_{out}-T_{in})
- Carnot Efficiency of the Engine η_c = 1-T3/TI
- Efficiency of a stirling engine η_s = 0.5* η_c ((PDF) Stirling Engines - G Walker (Oxford, 1980) WW - DOKUMEN.TIPS, n.d.)

- Power output is determined by considering the general relation of efficiency with power output and amount of heat supplied.

η_s=Power/Heat Supplied

Power output= η_s* Heat Supplied

COMPRESSION RATIO OF STIRLING ENGINE DRIVEN BY FLAT PLATE

0.071= [2077* (352.82-303) *Inr]/[2077* 352.82* Inr +{(1-0.8) *3133*(352.82-303)}]

0.071 = (103476* Inr)/(732807.14* Inr + 24.91)

r = 1.04

APPENDIX 4: PARABOLIC TROUGH

ANALYSIS

NOTATIONS

Absorber tube inner wall temperature = T_{w1}

Absorber tube outer wall temperature = T_{w2}

Water inlet temperature = T_i

Water tube outlet temperature = T_o

Ambient Temperature of air = T_∞

Length of tube = L

Glass tube diameter = d

Inner diameter of absorber tube = D_i

Outer diameter of absorber tube = D_o

Glass tube emissivity=ε

Specific heat capacity = C_p

Thermal conductivity = k

Density of water = ρ

Velocity of water = V

Kinematic Viscosity of water = μ

Heat Flux=q"

SPECIFICATIONS

Assume T_{w2}=70 °C

Tm= (70+20)/2

Tm= 45 °C

T_{w2}=80 °C

T_i=20 °C

T_∞=32 °C

T_o=unknown

D_o =0.07 m

D_i=0.059 m

$D=D_o-D_i$

D=0.07-0.059

D=0.011 m

L= 1.5 m

V=0.04 m/s

Properties of water at T_m=318K

C_p=4.180 kJ/kg

k=0.640 W/m²

ε=0.9

ρ=999.4 kg/m³

μ=577e-6

CALCULATIONS

i. Mass Flow Rate

m=ρ *A *V

m=ρ*x*(D²/4) *V

m=999.4*п* 0.011^2 * 0.04/4

m=$3.7e^{-3}$ kg/sec

ii. Nature of Flow

Re_D = (4*m)/ (п*(D_o + D_i) * μ

=(4*$3.7e^{-3}$)/ (п* (0.059 +0.07) * $577e^{-6}$

Rep=63.29 (<2300 i.e. laminar flow)

iii. For internal tubular laminar flow; the value of Nusselt No can be given as;

Nu_D = 5.42 (Incropera, DeWitt: Fundamentals of Heat and Mass Transfer, 5th Edition - Student Companion Site, n.d.)

iv. From the obtained value of Nusselt Number, coefficient of convection can be calculated in the following manner.

$h = (Nu_D * K)/D_i$

$= (5.42\ 0.640)/0.059$

$h = 58.79\ W/m^2$

v. According to the assumption no 8;

$q = q_{cond} + q_{conv}$

$q = \{(h * \pi D_o * L) * (T_{w2} - T_\infty)\} + [\{(2\pi * L*k) * (T_{w2} – T_{w1})\} / \{In (D_o - D_i)\}]$

$644 = \{(58.75* \pi*0.07*1.5) *(80-32)\} + [\{(2\pi*1.5* 0.64) * (80 – T_{w1})\}/ \{In (0.07/ 0.059)]$

$T_{w1} = 92.16\ °C$

vi. Tube outlet temperature now obtained by comparing Log Mean Temperature Difference with amount of heat convected in the tubes.

$T_o = (T_{w1} -(T_{w1} – T_i) \ln [- (\pi* D * L* h)/ (m* C_p)]$

$= 92.16- (92.16-20) \ln [-(\pi* 0.059 *1.5* 58.75)/ (3.7e^{-3} * 4180)]$

$= 67.06\ °C$

COMPRESSION RATIO OF STIRLING ENGINE OF PARABOLIC TROUGH

$0.142 = [2077* (423.366-303) *Inr] / [2077* 423.366* \ln r + \{(1-0.8) *3133*(423.366-303)\}]$

$0.142 = (250000* \ln r)/ (879331.182* Inr + 60.183)$

$r = 1.08$

APPENDIX 5

ADIABATIC FLAME TEMPERATURE OF CNG

From eq (5.2)

$\Sigma N_p*\{h_f^0+(h-h^0)\}_p = \Sigma N_r * (h_f^0)_r$

$H_{Reactant} = N_{CH4} * h_f^0{}_{CH4} + N_{O2} * h_f^0{}_{O2} + N_{N2} * h_f^0{}_{N2}$

$= 1 * (-74850)$

$= -74.850$ kJ .... eq (1)

$H_{Product} = N_{CO2}* \{h_f^0+(h-h^0)\}_{CO2} + N_{H2O}* \{ h_f^0+(h-h^0)\}_{H2O} +$

$N_{N2}* \{h_f^0+(h-h^0)\}_{N2}$

$= \{1*(-393520 + h_{CO2} – 9364)\} + \{2*(-241829 + h_{H2O} – 9904)\} +$

$\{7.52*(0 + h_{N2} – 8669)\}$ .... eq (2)

Eq (5.3) implies:

$h_{CO2} + 2h_{H2O} + 7.52\ h_{N2} = 896673$ kJ .... eq (3)

HEAT ENERGY EVOLVED FROM STIRLING ENGINE USING CNG AS AN ENERGY SOURCE

$Q = m_g * C_p * (T_3 – T_1)$

On Unit Mass Basis

Amount of heat supplied;

$Q = C_p * (T_3 – T_1)$

Rate of heat supplied on unit basis

$Q = 5.193 * (2328–303)$

$Q = 10.53$ kJ/kg

THEORETICAL EFFICIENCY OF STIRLING ENGINE USNG CNG AS AN ENERGY SOURCE:

$\eta_c= 1 – T_1/T_3$

$\eta_c= 1 - 303/2328$

$\eta_c=86.9\%$

Based on individual beliefs, it is possible to estimate a likely efficiency range of 40 to 50 percent for actual practices, in accordance with Carnot's efficiency principles.

One can determine the thermal efficiency of an engine by calculating the ratio:

$\eta_c = 0.5*(1 - T_1/T_3)$ ((PDF) Stirling Engines - G Walker (Oxford, 1980) WW - DOKUMEN.TIPS, n.d.)

$\eta_c = 0.5* 86.9$

$\eta_c = 43.45\%$

POWER OUTPUT OF STIRLING ENGINE USING CNG AS AN ENERGY SOURCE

η=Power/Heat supplied

$P = \eta * Q * rps$

Assuming 35% losses in the amount heat supplied to the engine;

Q = 6.84 kJ/kg

P = 0.434 * 6.84 * 6.66

P = 19.8 kW

COMPRESSION RATIO OF STIRLING ENGINE USING CNG AS AN ENERGY SOURCE:

$0.4345 = \{2077*(2328-303)*\ln r\}/[2077*2328\ln r+\{(1-0.8)*3133(2328-303)\}]$

$0.4345 = (4206*\ln r)/\{(4836*\ln r)+1012.5\}$

$r = 1.4$

APPENDIX 6: LIQUIFIED PETROLEUM GAS

ADIABATIC FLAME TEMPERATURE OF LPG

From eq (5.2)

$\Sigma N_p * \{h_f^0+(h-h^0)\}_p = \Sigma N_r * \{h_f^0+(h-h^0)\}_r$

$H_{Reactant} = N_{C3H8} * h_f^0{}_{C3H8} + N_{O2} * h_f^0{}_{O2} + N_{N2} * h_f^0{}_{N2}$

$= 1 * (-103628)$

$= -103.628$ kJ ....(3)

$H_{Product} = N_{CO2} * \{h_f^0+(h-h^0)\}_{CO2} + N_{H2O} * \{h_f^0+(h-h^0)\}_{H2O} +$

$N_{N2} * \{h_f^0+(h-h^0)\}_{N2}$

$= \{3*(-393520 + h_{CO2} - 9364)\} + \{4*(-241829 + h_{H2O} - 9904)\} +$

$\{18.8*(0 + h_{N2} - 8669)\}$ .... eq (4)

Eq (5.2) implies:

$3h_{CO2} + 4h_{H2O} + 18.8h_{N2} = 2378525.2 - 103628$

$3h_{CO2} + 4h_{H2O} + 18.8h_{N2} = 2274897.2$ kJ ....(5)

HEAT ENERGY EVOLVED FROM STIRLING ENGINE USING LPG AS AN ENERGY SOURCE:

$Q = m_g * C_p * (T_3 - T_1)$

On Unit Mass Basis

Amount of heat supplied;

$Q = C_p * (T_3 - T_1)$

Rate of heat supplied on unit basis

$Q = 5.193 * (2394 - 303)$

$Q = 10.85$ kJ/kg

EFFICIENCY OF STIRLING ENGINE USING LPG AS AN ENERGY SOURCE:

$\eta_c = 1 – T_1/T_3$

$\eta_c = 1 - 303/2394$

$\eta_c = 87.3\%$

The thermal efficiency of an engine can be calculated using a ratio, which may vary based on individual beliefs. For practical applications, a range of 40 to 50 percent of Carnot's efficiency is often assumed:

$\eta_c = 0.5*(1 – T_1/T_{3)}$

$\eta_c = 0.5* 87.3$

$\eta_c = 43.65\%$

POWER OUTPUT OF STIRLING ENGINE USING LPG AS AN ENERGY SOURCE:

η=Power/Heat supplied

$P=\eta*Q*rps$

Assuming 35% losses in the amount heat supplied to the engine;

Q = 7.052 kJ/kg

P = 0.436 * 7.052 * 6.66

P = 20.5 kW

COMPRESSION RATIO OF STIRLING ENGINE USING LPG AS AN ENERGY SOURCE:

0.4365 = {2077*(2394-303)*lnr}/[2077*2394*lnr+{(1-0.8)*3133*(2394-303)}]

0.4365 = (4343007*lnr)/{(4972338*lnr)+1045.5}

r = 1.45

APPENDIX 7: GASOLINE

ADIABATIC FLAME TEMPERATURE OF GASOLINE:

From eq (5.2)

$\Sigma N_p*\{h_f^0+(h-h^0)\}_p = \Sigma N_r * (h_f^0)_r$

$H_{Reactant} = N_{C8H18} * h_f^0{}_{C8H18}$

$= 1 * (-208500)$

$= -208500$ kJ ....(6)

$H_{Product} = N_{CO2}* \{h_f^0+(h-h^0)\}_{CO2} + N_{H2O}* \{ h_f^0+(h-h^0)\}_{H2O} +$

$N_{N2}* \{h_f^0+(h-h^0)\}_{N2}$

$= \{8*(-393520 + h_{CO2} – 9364)\} + \{9*(-241820 + h_{H2O} – 9904)\} +$

$\{47*(0 + h_{N2} – 8669)\}$ .... eq (7)

Eq (5.2) implies:

$8h_{CO2} + 9h_{H2O} + 47h_{N2} = 5896031–208500$

$8h_{CO2} + 9h_{H2O} + 47h_{N2} = 5687531$ kJ ....(8)

HEAT ENERGY EVOLVED FROM STIRLING ENGINE USING GASOLINE AS AN ENERGY SOURCE:

$Q = m_g * C_p * (T_3 – T_1)$

On Unit Mass Basis

Amount of heat supplied;

$Q = C_p * (T_3 – T_1)$

Rate of heat supplied on unit basis

$Q = 5.193 * (2409.8–303)$

$Q = 10.9$ kJ/kg

EFFICIENCY OF STIRLING ENGINE USING GASOLINE AS AN ENERGY SOURCE:

$\eta_c = 1 – T_1/T_3$

$\eta_c = 1 - 303/2409.8$

$\eta_c = 87.42\%$

Realistically, one may assume a probable value of 40 to 50 percent of the Carnot efficiency, depending on their viewpoint.

The ratio of power output to the amount of heat supplied may be used to determine the thermal efficiency of an engine.

$\eta_c = 0.5*(1 – T_1/T_3)$

$\eta_c = 0.5* 87.42$

$\eta_c = 43.71\%$

POWER OUTPUT OF STIRLING ENGINE USING LPG AS AN ENERGY SOURCE:

η=Power/Heat supplied

$P=\eta*Q*rps$

Assuming 35% losses in the amount heat supplied to the engine;

Q = 6.84 kJ/kg

P = 0.437 * 6.84 * 6.66

P = 19.9 kW

COMPRESSION RATIO OF STIRLING ENGINE USING LPG AS AN ENERGY SOURCE:

0.4371 = {2077*(2409.8-303)*lnr}/[2077*2409.8*lnr+{(1-0.8)*3133*(2409.8-303)}]

0.4371 = (4205925*lnr)/{(4835256*lnr)+1012.5}

r = 1.3