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DESIGN AND FABRICATION OF A SOLAR ADSORPTION REFRIGERATION CYCLE

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CERTIFICATION

This is to certify that this project work, Design and Fabrication of Solar Vapor Adsorption Refrigeration System was carried out by **DEBRA EFEOGHENE (ENG2002431), CHIMEZIEM MERIT (ENG2006373), ALPHA CHRISTABEL (ENG2002425), OBASOGIE DIVINE (ENG2002479), IZOBEMHE RADIANCE (ENG2103122), OBASOGIE DENNIS (ENG2002480), OKOSE MERIT (ENG2006384) and IZEHIESE MARY (ENG2002485)** of the department of Mechanical Engineering, Faculty of Engineering, University of Benin, in partial fulfillment of the requirements of the award of the Bachelor of Engineering (B.Eng.) Degree in Mechanical Engineering.

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DEDICATION

This report is dedicated to God, the source of Life and Wisdom. We sincerely thank our parents, loved ones, and supporters, whose steadfast presence has been a constant source of encouragement, especially during difficult moments. Their love and faith in us have given us the strength and determination to see this project through to completion. We deeply appreciate their continuous support, which has been crucial to our academic and personal development.

ACKNOWLEDGMENTS

We are profoundly grateful to the Almighty God for making our journey possible. We would also like to extend our sincere thanks to Engr. Martin, our Project Supervisor, whose dedicated efforts greatly helped in the completion of this report. His support and guidance were valuable to us throughout the entire project. We also wish to thank the Head of Department, of Mechanical Engineering, Prof P.O.B Ebunilo for providing an environment conducive for research and the successful completion of this project. Our gratitude extends to all the lecturers whose teachings have enriched our knowledge over the years.

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NOMENCLATURE

VCRS – Vapor Compression Refrigeration Systems

VARS – Vapor Absorption Refrigeration System

COP – Coefficient of Performance

NH_3 - Ammonia

CO_2 – Carbon dioxide

CO – carbon mono-oxide

H_2O - Water

PV- Photovoltaic cell

PTCS – Parabolic Trough Collectors

DNI – Direct Normal Irradiance

CFCs - Chloroflorocarbon

HFCs - Hydroflorocarbons

CAD – Computer Aided Design

ABSTRACT

The problem of electricity in Nigeria has become some sort of a nationwide pandemic that has plagued the country for years and continues to do so. With seemingly no end in sight to the electricity crisis, food storage has become very expensive as individuals as well as producers need to pay a lot of money to run generators to power refrigerators. An alternative means to this would be a more than welcomed development. This project aims to reduce the cost encountered in refrigeration by using vapor absorption refrigeration which is powered by solar energy.

The vapor absorption refrigerator uses water as its refrigerant, and zeolite is used as the absorbent. The compression system is a network of systems consisting of an absorber and a generator; aimed at compressing liquid refrigerant-absorbent mixture which requires less work to compress than vapor. The temperature of the evaporator, generator and condenser were measured and recorded periodically. The performance of the system is evaluated as the ratio of heat removed from the refrigerated space to the heat added to the system at the generator.

The refrigerator proved quite functional, achieving a COP of 0.66. This validates the functionality of the system but it was observed that it took 3 hours of heating to produce a 9°c drop (from 34.2°c to 25.2°c) in evaporator temperature. After 5 hours of heating, there was a 15°c drop (from 34.2°c to 19.2°c) in evaporator temperature. However, the atmospheric temperature was 27°c which means the cooling achieved was not appreciable. The system used in this project suffered from a lot of leakages and heat loss which directly affected the performance of the system. We recommend that further studies on techniques which would prevent heat loss and meticulous fabrication process to prevent leakages allow. Significant reduction in heat loss would greatly improve the performance of the waste solar powered VARS thereby making it more viable and suitable for domestic and commercial usage

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Refrigeration is a term used to describe a process which maintains a space or material at a temperature less than the ambient temperature. Cooling is achieved by removing heat from an object or space using a refrigerant that absorbs thermal energy, allowing heat to move from a warmer object to a colder object or area. Historically, natural techniques such as evaporative cooling with clay pots and storing ice from rivers or mountains were used to preserve perishables. The Romans, transported snow from the Alps to cool drinks. Over time, scientific and engineering progress led to the development of artificial refrigeration systems that offer more reliable and efficient cooling.

The idea of utilizing solar energy to operate a refrigeration system date back several decades, with early developments emerging around forty years ago through prototypes based on liquid adsorption cycles, as noted by (Sumathy, 1999). Over the past twenty years, adsorption-based refrigeration has gained considerable attention as a feasible alternative to conventional vapor compression systems, largely due to its potential for reducing environmental impact and energy consumption.

In addition to liquid adsorption, solar refrigeration systems can also employ solid adsorption techniques, which function through either physical adsorption or chemical reactions. Several experiments have confirmed that solid-gas adsorption systems are particularly well-suited for simple, low-maintenance applications. These systems utilize renewable energy and are often free of moving mechanical parts and can function effectively using low-grade thermal energy, such as waste heat or solar heat, making them ideal for sustainable cooling solutions.

In recent decades, solar-powered refrigeration and air-conditioning have become increasingly appealing, particularly because peak solar availability often coincides with high demand for cooling. Among the various applications, solar ice production is considered especially efficient. Ice, with its high latent heat capacity, allows thermal energy to be stored in compact volumes, enabling the design of smaller refrigeration units.

Solid adsorption refrigeration systems capitalize on the unique thermodynamic behavior of specific adsorbent refrigerant combinations, enabling them to complete cooling or heat pump cycles without the need for compressors or electrical inputs. Materials such as zeolite and activated carbon have been widely used as adsorbents. Ing (2004) recommended that the pairing of zeolite and water is particularly effective for achieving a cooling effect, while the combination of activated carbon and methanol is suitable for a solar driven solid adsorption ice-maker.

1.2 STATEMENT OF THE PROBLEM

In an optimal setting, communities across Nigeria would have access to dependable infrastructure that ensures the smooth functioning of everyday needs, including refrigeration. This would not only involve consistent electricity but also the availability of affordable refrigeration units and efficient supply chains for cooling-dependent goods. In such a scenario, both urban and rural populations could safely store food, preserve agricultural produce, and maintain the cold chain for medicines and vaccines, contributing to better health, reduced waste, and enhanced food security nationwide.

In reality, however, many rural communities in Nigeria remain disconnected from the national grid, while urban areas experience frequent blackouts. These power challenges make it difficult to rely on conventional refrigeration systems. Although solar-powered refrigerators using mechanical components exist, their high cost places them out of reach for most households and small clinics, especially in remote regions.

To bridge this gap, a more affordable and sustainable alternative lies in solar adsorption refrigeration systems using a compatible adsorbate-adsorbent pair (e.g. zeolite-water) as working materials. Operating on solar thermal energy rather than electricity, these systems are well suited to Nigeria's sunny climate and can function independently of the grid. Their application will be particularly valuable in preserving vaccines and perishable goods in underserved areas. By embracing this low-cost, environmentally friendly solution, Nigeria can significantly improve access to dependable cooling in regions where it is most required.

1.3 AIM

The aim of the project is to design and fabricate a solar powered cooling system using renewable solar energy source.

1.4 OBJECTIVES

The objectives of the project are as follows:

i. To design and fabricate a cost-effective prototype of a solar adsorption system.
ii. Enhance cooling needs in areas with limited electricity.
iii. Selecting suitable adsorbent material to be used.
iv. Promoting sustainability for cooling needs through efficient harnessing of solar energy.
v. Utilizing an eco-friendly source of cooling.

1.5 THE SCOPE OF PROJECT

This project focuses on the design and fabrication of a solar-powered adsorption refrigeration system that provides affordable, sustainable and eco-friendly cooling, suitable for off-grid or low-energy applications; it entails analyzing and evaluating different working pairs and solar energy harnessing methods optimal for this purpose.

Key aspects covered by this project include:

i. A comprehensive study of refrigeration systems, beginning with an in-depth exploration of adsorption refrigeration principles and their operational cycles. Various adsorbateadsorbent pairs such as zeolite-water pair, activated carbon-methanol, and lithium bromide-water are assessed based on performance, environmental impact, and system suitability. From this evaluation, the zeolite-water pair is selected for its favorable thermodynamic characteristics, chemical stability, and non-toxic nature.
ii. This project also encompasses the detailed design of core components such as the solar collector, adsorption bed, condenser, and evaporator. This includes the calculation of critical parameters like optimal collector area and adsorption bed size to ensure effective heat transfer and reliable system operation. Material selection for each component is guided by factors and criteria such as thermal conductivity, durability, cost-effectiveness, and compatibility with the working pair to maximize efficiency and system longevity. iii. This project also entails the fabrication of the system by assembling each component in accordance with functional and structural requirements from the design and materials acquired. The completed unit is then subjected to operational testing under real conditions,

with performance evaluated using key metrics including cooling capacity, coefficient of performance (COP), and overall system efficiency.

1.6 SIGNIFICANCE OF PROJECT

The significance of this project lies in its innovative approach to providing sustainable and environmentally friendly refrigeration through the use of solar-powered adsorption technology. By utilizing solar thermal energy instead of electricity or fossil fuels, this system offers a reliable cooling solution that is especially valuable in off-grid and rural areas where access to conventional power sources is limited or unavailable. The integration of solid adsorbent materials, such as zeolite or activated carbon, with natural refrigerants like water or methanol, allows for an efficient and eco-conscious refrigeration cycle that produces no harmful emissions and uses no moving parts, thereby reducing maintenance needs and extending system lifespan. This project supports global efforts toward renewable energy adoption by offering a practical alternative to vapor compression systems, which typically rely on synthetic refrigerants with high global warming potential. Through the design, material selection, and fabrication of a working prototype, the project demonstrates the feasibility of low-cost, solar-driven cooling technologies for real-world applications such as food preservation, medical storage, and domestic use in energy-scarce regions. It also contributes to educational and research development by incorporating multidisciplinary principles in thermodynamics, heat transfer, mechanical design, and renewable energy integration. The project provides a replicable framework that can serve as a foundation for future innovations in clean cooling systems and supports long-term sustainability goals.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION TO THE REFRIGERATION CYCLE

The refrigeration cycle is a process where a working fluid, called the refrigerant, goes through a series of steps in a specific order to produce cooling. As mentioned earlier, the refrigeration cycle works in the opposite way to a Brayton power cycle. For power cycles, the most efficient ideal process is known as the Carnot Cycle. Similarly, for refrigeration, the most efficient and ideal process is called the Reversed Carnot Cycle. This cycle consists of two reversible constant temperature processes and two isentropic processes, but it has several practical limitations that make it difficult to use in real-life applications. To address these limitations, the ideal vapor compression refrigeration cycle was developed, offering a more practical and widely used solution.

In this reversed Carnot cycle, the refrigerant first enters the compressor in a gaseous state, where it is pressurized to a higher level. This raises both its pressure and temperature to the point needed for condensation. The hot, high-pressure refrigerant then flows into the condenser, where it releases heat (first its superheated heat and then its latent heat) either to the surrounding air or to a cooling medium. This process changes the refrigerant from a gas to a liquid. Next, the liquid refrigerant passes through an expansion valve, where it undergoes a sudden drop in pressure. This rapid expansion also causes its temperature to fall below that of the refrigerated space. Finally, the cold, low-pressure refrigerant moves into the evaporator, where it absorbs heat from the refrigerated area and fully evaporates back into a gas.

2.2 REFRIGERATION SYSTEMS

A refrigeration system is a complex network of components that work together to remove heat from a specific space or substance, resulting in lower temperatures. Over the years, different refrigeration systems have been developed, each working on distinct principles and suited for specific applications. Some of these refrigeration systems include;

i. Vapor Compression Refrigeration System (VCRS)

The vapor compression refrigeration cycle is shown in figure 2.1 below

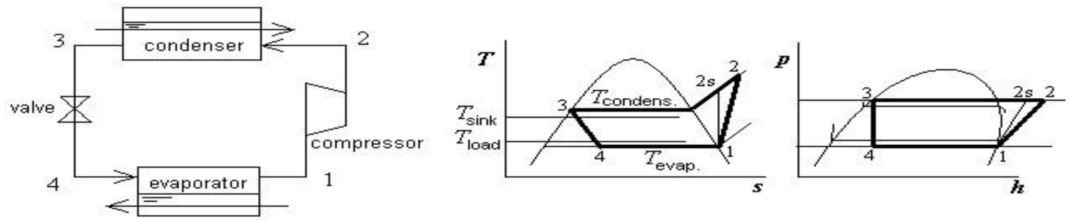

figure 2.1 **Vapor compression refrigeration cycle**

Vapor compression refrigeration is a widely used method for cooling; it relies on the evaporation of a volatile liquid under reduced pressure to absorb heat from the environment. This cycle is based on a modified reverse Rankine process. While typically using pure refrigerants for stability, some systems use mixtures to enhance performance. Despite their efficiency and widespread application in homes, industries, and commercial spaces, these systems depend heavily on electricity and often use synthetic refrigerants that contribute to environmental issues such as ozone layer depletion and global warming.

ii. Vapor Adsorption Refrigeration System (VARS)

The Adsorption refrigeration cycle is shown in figure 2.2 below

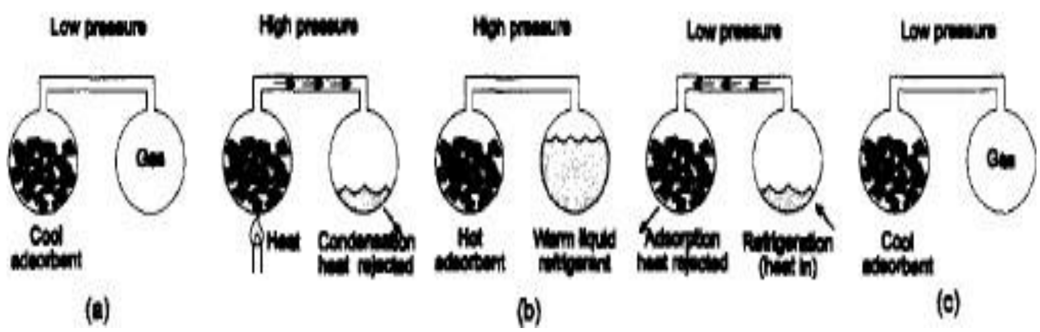

figure 2.2 **Adsorption Refrigeration Cycle**

An adsorption system works by attracting and accumulating gas or liquid molecules (adsorbate) onto a solid surface (adsorbent bed) through physical forces like Van der Waals interactions.

This process doesn't alter the adsorbent's structure and is most effective when the material has a large surface area and porous structure.

In adsorption refrigeration, no mechanical compression is used but the adsorbent acts as the chemical compressor' driven by heat. The cycle includes two phases: adsorption, where the vapor is absorbed, and desorption, where heat drives the vapor off to condense and release heat. Systems can operate intermittently (cooling at night, regeneration during the day) or continuously using multiple adsorbent beds Critoph (1999). Using dual beds improves efficiency, enabling continuous and renewable cooling. This is the type of refrigeration system under consideration in this study

2.3 VAPOR ADSORPTION REFRIGERATION

Adsorption refrigeration technology has roots in the mid-19th century, beginning with Edmond Carré's absorption system using water and sulphuric acid, followed by Ferdinand Carré's 1858 design that used water and ammonia. Unlike the vapor compression refrigeration system (VCRS), which relies on a mechanically driven compressor to circulate refrigerant, the vapor absorption and adsorption systems use heat energy to drive the cycle. In these systems, the compressor's function is replaced by an absorber and generator, where the refrigerant is separated from its absorbent using heat from sources like solar energy, waste heat, or low-cost fuels.

While VCRS is powered by electricity, adsorption refrigeration thrives where inexpensive or renewable heat is available, though it typically has a lower coefficient of performance (COP). Research from the 1980s onward has explored various adsorbent–adsorbate pairs, with zeolite–water and activated carbon–methanol being common. Across decades of experimentation; zeolite–water has emerged as a leading choice for its environmental safety, durability, and suitability for sustainable refrigeration.

2.3.1 Components of an Adsorption Refrigeration System

The vapor absorption refrigeration system is made up of the following main parts, as explained by Gevariya et al. (2016):

i. **Generator:** After the absorbent has adsorbed the refrigerant, a strong adsorbent-adsorbate pair is formed .The strong solution is heated using an external heat source (e.g solar thermal heat or waste energy heat) in the generator. This heating increases the temperature, causing the refrigerant to evaporate out of the solution. It leaves at high pressure and temperature and flows into the condenser to be cooled.

ii. **Condenser:** The refrigerant enters the condenser as a hot and high-pressure gas. It releases heat to the surroundings and condenses to a saturated liquid.

iii. **Expansion valve (or restriction):** As the refrigerant passes through this valve, its pressure drops suddenly. It then enters the evaporator at low pressure and temperature, keeping the enthalpy at the condenser exit equal to the enthalpy at the evaporator entry.

iv. **Evaporator:** The refrigerant, now at low pressure and temperature, absorbs heat from the area or substance to be cooled. This is where the cooling effect happens. Unlike the vapour compression system, where the compressor draws the refrigerant, here it flows back into the absorber.

v. **Absorber:** This is a container which holds the absorbent mixed with the refrigerant already absorbed earlier. The mixture in the absorber is a weak solution of absorbent and refrigerant. When more refrigerant enters from the evaporator, the absorbent bed quickly adsorbes it, which lowers the pressure inside the absorber. This pressure drop encourages more refrigerant to flow in from the evaporator. As the refrigerant is absorbed, its volume reduces, which is similar to compression. The process also produces heat, which is removed using an external cooling medium.

2.4 ADSORBENT-ADSORBATE PAIRS

The type of adsorbate (refrigerant) and the matching adsorbent used in an absorption refrigeration system depends mainly on the required evaporator temperature. The refrigerant should have a high latent heat of evaporation so it can absorb more heat during phase change, and its molecules should be small enough to make adsorption easier.

Water is often chosen as the refrigerant because of one outstanding property, which is its very high enthalpy of vaporization, which is about 2438 kJ/kg at 25°C. When water is used as the adsorbate, zeolite is a common and suitable adsorbent because of its strong ability to take in water vapor.

A refrigerant is any substance that can take heat from a source (such as a cooled space or object) and release it to another location (the heat sink, usually the surrounding environment). This heat transfer may occur as sensible heat (temperature change) or latent heat (phase change) (Gevariya et al., 2016). For an absorbent-adsorbate pair to work well in a vapor absorption system, the following conditions should be met (Gevariya et al., 2016):

The refrigerant must be adsorbed well in the absorbent bed.

i. Their boiling points should differ enough so that in the generator, only the refrigerant boils off, ensuring that pure refrigerant moves through the rest of the system.
ii. The heat released during mixing should be low to maintain a high coefficient of performance (COP). iii. The mixture should have good thermal conductivity and low viscosity for efficient heat and mass transfer.

iv. It must not form crystals or solidify inside the system.
v. It should be safe to handle, chemically stable, non-corrosive, affordable, and easy to obtain.

There are several adsorbent-adsorbate pairs; each with their unique features and applications, they include:

i. Activated-Carbon-Methanol: This pair has been widely studied because methanol evaporates easily at low temperatures, making it useful for ice-making and small-scale refrigeration. However, methanol is flammable and toxic, which limits its safety in practical applications.
ii. Activated-Carbon-Ammonia: This combination is suitable for low-temperature applications such as food preservation and freezing. Ammonia provides strong refrigerating capacity, but its corrosive and toxic nature requires careful system design and handling.
iii. **Silica Gel-Water**: Silica gel paired with water works effectively in air conditioning and moderate cooling systems. It operates at relatively low regeneration temperatures (around 60– 90°C), which makes it compatible with flat plate solar collectors. The limitation is that it cannot reach very low temperatures, making it unsuitable for freezing.
iv. Zeolite-Water: Zeolite has a strong affinity for water vapor, allowing the system to operate at high adsorption capacity even under low partial pressures. This makes it particularly effective in solar-powered refrigeration, where reliable performance under varying

conditions is needed. It also offers excellent environmental safety since both water and zeolite are non-toxic.

The zeolite-water pair has been chosen for this project due to the reasons analyzed below;

2.4.1 Zeolite

The name "Zeolite" was first introduced in the 18th century by a Swedish mineralogist named Cronstedt, who noticed that when a natural form of the mineral was heated quickly, it released water vapor and appeared to move or "dance." Inspired by this observation, he combined Greek terms meaning "boiling stone" to create the name Zeolite. Zeolites are most commonly described as crystalline aluminosilicates that possess a cage-like framework. More precisely, a Zeolite is a hydrated crystalline aluminosilicate with a porous structure that houses water molecules and exchangeable cations. These components are loosely held within the framework, enabling ion exchange and reversible moisture absorption, categorizing Zeolites as molecular sieves. For context, the pore size of dried Zeolite is about 6 Ångstroms, compared to 50 Å in silica gel and 105 Å in activated carbon

To this date, scientists have synthesized over 150 types of Zeolites, in addition to around 40 naturally occurring varieties. They exist in hydrated forms and share the basic chemical ratio of at least one silicon atom per aluminum atom, commonly expressed as $\mathbf{Al_2O_3 \cdot 2SiO_2 \cdot 4.5H_2O}$. Most Zeolites can release their water content gradually within a temperature range of 150 to 400 °C without losing the integrity of their structure. They are also able to reabsorb moisture from the air at ambient conditions. As molecular sieves, Zeolites can selectively adsorb specific molecules based on their shape, size, or charge, making them highly useful in various adsorption and filtration applications.

Zeolite possesses several key features that make it valuable in refrigeration applications, they include:

i. **They Easily Lose and Regain Water:**

Zeolite can be thoroughly dehydrated and will readily release water when heated. This ability is critical for applications like refrigeration and drying processes, where reversible adsorption is needed.

ii. **Lightweight With High Porosity When Dry:**

Dehydrated Zeolite becomes low in density and has a large internal void space. This structure makes them efficient for storing and trapping molecules, enhancing their use in gas separation and adsorption.

iii. **They Have Strong Structural Integrity When Dry:**

After losing water, Zeolite still maintains the stability of their crystalline framework. This makes them durable and reusable in repeated adsorption-desorption cycles.

iv. **Consistent Pore Size Within the Crystal Structure:**

The molecular channels within dehydrated Zeolite are uniform in size, allowing them to selectively adsorb molecules based on size; hence their classification as molecular sieves.

v. **Effective in Adsorbing Gases and Vapors:**

Due to its porous nature, Zeolite can adsorb a variety of gases and vapors, making them useful in air filtration, odor removal, and gas separation technologies.

2.4.2 Water

In 1980, Tchernev established that within the temperature range of 0 to 10°C, water vapor delivered the most efficient performance in adsorption-based cooling systems. Zeolites, commonly used as adsorbents, can typically hold around 20% of their weight in water. Water stands out among refrigerants due to its high latent heat of vaporization (approximately 2330 kJ/kg) significantly surpassing values for alcohols and ammonia (about 1160 kJ/kg) and halocarbon-based refrigerants (around 230kJ/kg). Water vapors also maintain chemical stability when exposed to zeolite even at elevated temperatures reaching 200°C.

Although water's freezing point at 0°C might initially suggest limitations for sub-zero evaporator applications, this is not necessarily the case. Water continues to evaporate in its solid form due to its measurable vapor pressure at temperatures below -20°C. This allows for continued adsorption-based cooling, even when the water is frozen. Adding salts to the water to depress its freezing point permits the sustained evaporation of liquid water at even lower temperatures. These characteristics enable the water-zeolite adsorption system to deliver effective cooling capabilities below -20°C, as also observed by Schwarz in 1994.

2.5 VAPOR ADSORPTION CYCLE DEVELOPMENT

The coefficient of performance (COP) of a refrigeration system is defined as the amount of cooling provided to the refrigerated space compared to the amount of work supplied to operate the system (Manojprabhakar, 2014). It is a key measure used to describe how well refrigeration systems in general perform (Suraj, 2013).

$$\mathrm{COP}_{\mathrm{cooling}} = \Delta Q_{cold} / \Delta W_{in}$$

In practical absorption refrigeration systems, the coefficient of performance is generally below 1 (Cengel et al., 2006). Although their COP is lower than that of vapor compression refrigeration (VCR) systems, absorption systems are often chosen when there is access to low-cost waste heat from industrial processes or renewable sources such as solar or geothermal energy (Prakash, 2017).

Due to the fact that the COP of the VAR system is quite low, many researchers have explored different heat energy sources to drive the system and conducted economic evaluations, as outlined below:

2.5.1 Geothermal Vapor Adsorption Systems

Geothermal energy is a renewable and sustainable form of energy that can be applied in many heat-driven processes (Tesha, 2009). It comes from the natural heat stored within the Earth, which is generated by radioactive decay and the gradual release of heat from the planet's formation (Schubert, 2002). For centuries, people have taken advantage of geothermal systems, such as using hot springs for bathing and other purposes (Schultz, 2018). The concept of extracting heat from the ground for practical use began in 1912, when Zoelly developed the first geothermal heat pump (Schultz, 2018). Today, geothermal energy is mainly used in heat pumps, direct heating for homes and buildings, and electricity generation (Lund, 2019). However, it can also be applied in refrigeration.

When steam is extracted during the separation of geothermal fluid mixtures, a portion of the heat produced is low-grade thermal energy, often considered waste heat. Depending on its temperature and energy content, this waste heat (for example, from geothermal brine water) can be harnessed to run absorption refrigeration systems, meeting various cooling and refrigeration needs (Tesha, 2009). Geothermal renewable energy source stands out as one of the most reliable with minimal environmental impact. It has the highest capacity factor and is regarded as an excellent thermal energy source for powering VAR systems (Suraj et al., 2013). In El Salvador, researchers proposed and examined the use of geothermal energy in refrigeration and cooling technologies based on the absorption cycle, offering an eco-friendly solution for preserving food products (Juan Carlos, 2007).

2.5.2 Natural Gas or LPG based Adsorption Refrigeration Systems (Kerosene)

Kerosene-powered absorption refrigerators became popular in the early 20th century as a reliable cooling option for rural and off-grid areas. They were especially useful in places without electricity or steady gas supply, since they only needed kerosene to run. Brands like the Perfection Stove Company manufactured these units for domestic use, often promoting them as maintenance-free and silent compared to compressor-driven models. They were common in farmhouses, remote trading posts, and even early expedition camps, providing safe food storage where no electrical infrastructure existed.

In this type of refrigerator, a mixture of ammonia and water is held in the generator, beneath which kerosene burners are positioned. When the burners are lit, the heat they produce causes the ammonia to separate from the solution and move upward through a pipe into a coil placed inside a water container located at the top of the refrigerator. The surrounding water cools the coil, causing the hot ammonia vapor to condense into a high-pressure liquid. This liquid flows into the receiver and then enters the cooling section, or evaporator, where it evaporates again, absorbing heat from the refrigerated space and creating the cooling effect. The process continues for as long as the kerosene in the burner lasts.

2.5.3 Solid Waste Energy Adsorption Systems

Waste refers to materials that contain a mix of organic matter, metals, minerals, water, and other substances. Energy recovery from waste simply means generating usable heat or electricity from waste treatment (Sunethra, 2016). Around the world, solid waste management is a significant challenge, and the situation is even more critical in developing countries like Nigeria (Ebikapade and Jim, 2016). In Nigeria, waste management is hindered by poor collection systems and unsafe disposal practices (Ogwueleka, 2009). Collection efficiency ranges from as low as 5% in some semi-urban areas to about 50% in major cities, and the amount of waste being produced is increasing faster than the ability of waste management agencies to expand their capacity (Ityona, 2012). This makes it important to explore approaches that improve waste collection, processing, and utilization in the country. Solid waste typically contains both organic and inorganic materials, with organic matter making up the larger portion (Patil et al., 2014). The energy stored in the organic fraction can be recovered using suitable waste processing and treatment technologies, which not only generate useful energy but also reduce waste volume by more than 90%, lower environmental pollution, and save land that would otherwise be used for dumping. Since much of this waste consists of renewable materials like paper, food scraps, wood, cotton, and leather, it can serve as a renewable energy source (Paula, 2006). Thermal treatment methods for energy recovery include pyrolysis, gasification, and combustion, each involving different processes for breaking down waste materials (Claudine, 2012).

Combustion remains the most established method for converting solid waste into usable energy and has been in practice for over a century (Stantec, 2011). It involves burning carbon-based waste in a high-temperature, oxygen-rich environment, producing heat along with gases mainly composed of carbon dioxide (CO_2) and water vapour (H_2O) (Moustakas, 2010). The efficiency of heat recovery depends on factors such as waste density, composition, moisture content, and combustion system design, with practical recovery rates ranging between 65% and 80% of the waste's energy content (Patil et al., 2014). The overall process performance is influenced by the physical and chemical properties of the waste material, including size, bulk density, heat content, and calorific value (Obernberger, 2006). The most important measure of potential energy recovery is the higher calorific value (also known as higher heating value or gross calorific value), which represents the maximum thermal energy obtainable per unit mass when combustion is complete and all water present or produced remains in liquid form (Olisa and Ajoko, 2018; Carlos et al., 1991).

2.5.4 Solar Adsorption Refrigeration System

Solar radiation has been harnessed by humanity for centuries, beginning with passive solar heating in ancient Greek and Roman buildings and progressing through pioneers like Horace-

Benedict de Saussure's early solar collectors in the 18th century and 19th-century breakthroughs in the photovoltaic effect by Becquerel, Fritts, and later the first practical silicon solar cell by Bell Labs in 1954. Today, Nigeria lies in a prime spot for solar energy use, receiving an average daily sunlight of roughly 5.4 $kWh/m^2/day$, with the northern regions reaching up to 7 kWh/m^2 daily. This vast and easily accessible resource is ideal for meeting the country's energy needs; especially in areas without reliable grid access, but to truly benefit, we must invest in low-cost, scalable ways to capture and use this sun power effectively. Sunlight delivers about 1.73×10^{17} W to Earth at any given time which is thousands of times more than current human energy use; making it one of the truly unlimited primary energy sources. It generates no direct greenhouse gases or radioactive waste, making it far cleaner than fossil fuels or nuclear power. Rapid advances in cost reduction and deployment of solar technologies now strengthen the case for using solar heat directly, especially where other fuels are costly or unreliable.

Solar-powered refrigeration uses heat from the sun to drive a thermodynamic cycle, often through solar thermal collectors or concentrators that capture and convert sunlight into thermal energy. This heat is directed to a generator or adsorber containing a refrigerant–adsorbent pair, initiating the separation process by raising the refrigerant's temperature and pressure. The hot refrigerant vapor is then condensed in a heat exchanger, typically cooled by ambient air or water, producing a high-pressure liquid. This liquid flows into the evaporator, where it vaporizes at low pressure, absorbing heat from the refrigerated chamber and creating a cooling effect. The cycle operates as long as sufficient solar heat is supplied, and surplus thermal energy can be stored in phase change materials or hot water tanks for nighttime or cloudy-day operation. The efficiency and performance depend on factors such as collector type, solar intensity, thermal storage capacity, and system design. It generates no direct greenhouse gases or radioactive waste, making it far cleaner than fossil fuels or nuclear power. Rapid advances in cost reduction and deployment of solar technologies now strengthen the case for using solar heat directly, especially where other fuels are costly or unreliable with available sunlight, such as Nigeria. This is the energy source under consideration in this study.

Solar energy can be harnessed for refrigeration using different methods:

i. **Use of photovoltaic cells**

One approach to harness solar energy for adsorption refrigeration is through the use of photovoltaic (PV) cells. In this method, solar radiation is directly converted into electrical energy using PV modules. The generated electricity is then supplied to a resistive heating element, which in turn provides the thermal energy required to drive the adsorption cycle. The heating element transfers this heat to the generator, where it raises the temperature of the adsorbent– adsorbate pair, causing the refrigerant to desorb from the adsorbent material. This design offers flexibility in operation since electrical energy from the PV array can be stored in batteries for later use, ensuring the system can operate during periods of low or no sunlight. The use of electrical heating allows for precise temperature control, improving system efficiency and performance compared to direct solar thermal heating, which is more dependent on weather fluctuations but it is not cost efficient.

ii. **Use of flat plate / Evacuated tube solar collectors**

Solar thermal collectors are another effective way of harnessing solar energy for adsorption refrigeration systems, converting sunlight directly into heat to drive the desorption process. Two common types are flat plate collectors and evacuated tube collectors. Flat plate collectors consist of a dark absorber plate enclosed in a transparent cover, which traps solar radiation and transfers the heat to a working fluid, usually water or a water–glycol mixture. They are cost-effective, mechanically simple, and suitable for moderate temperature ranges typically required for adsorption refrigeration. Evacuated tube collectors, on the other hand, use a series of glass tubes with a vacuum layer that greatly reduces heat losses, allowing them to achieve higher operating temperatures and maintain efficiency even in cooler or windy conditions. In both cases, the heated working fluid is circulated to the generator of the adsorption system, where it supplies the thermal energy needed to release the refrigerant from the adsorbent. This direct thermal approach avoids the conversion losses associated with photovoltaic systems, making it a more efficient method when consistent solar heat is available.

iii. **Use of parabolic trough**

Parabolic trough collectors are a type of concentrating solar technology capable of supplying the high temperatures needed for adsorption refrigeration. They use long, curved reflective surfaces shaped like a parabola to focus sunlight onto a linear focal point. In this project, the focal line is aligned directly with the generator containing the adsorbent–adsorbate mixture, allowing concentrated sunlight to heat it without using a separate heat transfer fluid. This direct-heating method reduces thermal losses, improves overall efficiency, and lowers system complexity. Parabolic troughs are also relatively cost-efficient compared to other high-temperature solar concentration methods, making them a practical choice for small- to medium-scale adsorption systems. For these reasons, this approach has been selected for our project to achieve reliable and efficient thermal input for the refrigeration cycle.

2.6 SOLAR ADSORPTION REFRIGERATION SYSTEM UTILIZING PARABOLIC TROUGHS

Parabolic trough collectors (PTCs) have been in use since the early 20th century, initially developed for industrial heat applications and later finding widespread use in solar thermal power generation during the 1970s energy crisis. Their ability to concentrate solar radiation onto a focal line allowed them to deliver significantly higher temperatures than conventional flat plate or evacuated tube collectors, making them attractive for a range of thermal processes. Over the past few decades, research has extended their application to thermally driven refrigeration systems, including adsorption refrigeration cycles. Studies from the late 1990s onward demonstrated that PTCs could reliably provide the generator temperatures needed for adsorbent– adsorbate pairs such as zeolite–water and activated carbon–methanol, enabling efficient solarpowered cooling (Hernández et al., 2019; Li et al., 2021).

For this project, the parabolic trough will be configured to focus sunlight directly onto the generator containing the adsorbent–adsorbate mixture, eliminating the need for an intermediate heat transfer fluid. This direct-heating approach reduces thermal losses, simplifies system design, and lowers operational costs. In regions with high direct normal irradiance (DNI), PTCs can provide a stable and continuous thermal input during sunlight hours, enabling refrigeration without dependence on grid electricity.

2.6.1 Advantages of using Parabolic Trough for Adsorption Refrigeration

i. **High Operating Temperatures**: PTCs can reach temperatures above 150°C, which is more than sufficient for driving most adsorption refrigeration cycles. This makes them more versatile than non-concentrating collectors.

ii. **Improved Thermal Efficiency**: By concentrating sunlight onto a small area, PTCs reduce heat losses and achieve higher thermal efficiencies compared to flat plate or evacuated tube collectors.

iii. **Direct Heating Capability**: In this project, the PTC will directly heat the generator, eliminating the need for a heat transfer fluid and its associated pumping losses. This simplifies the design and improves overall efficiency.

iv. **Cost-Effectiveness**: When designed and manufactured locally, PTCs can be relatively cost-efficient compared to other high-temperature solar concentration methods such as solar towers or dish collectors.

v. **Suitability for Rural and Off-Grid Areas**: Since PTCs operate purely on solar energy, they can be deployed in remote areas with limited or no grid access, providing sustainable refrigeration without reliance on fossil fuels.. The parabolic

trough collector has been selected as the primary solar heat source for this project due to the numerous advantages above, with the design tailored for direct heating of the generator to achieve efficient and reliable operation.

2.6.2 Applications Of Solar Powered Vapor Adsorption Systems

i. These systems are suitable for facilities experiencing high electrical demand charges, as using absorption chillers helps to significantly reduce peak loads in the building's electrical consumption profile.

ii. They are applicable in locations where the relative cost of electricity compared to fuel oil or gas makes fuel the more economical choice. Research indicates that in many regions, the difference in energy costs between gas and electricity makes absorption systems financially advantageous.

iii. They are also valuable in areas with limited or no access to electricity. Since absorption refrigeration systems can operate without electrically driven components, they are highly beneficial in electricity-scarce regions.

iv. Solar adsorption refrigeration systems can maintain low temperatures for storing vaccines and other temperature-sensitive medicines in rural health centres where electricity supply is unreliable.

CHAPTER THREE

MATERIALS AND METHODS

3.1 CONCEPTUAL DESIGN

This project was undertaken in order to meet the need of refrigeration in areas with inadequate electricity supply and to proffer a cheap substitute means for commercial and household refrigeration. In the design of this refrigerator system, the vapor absorption was selected (since the work input to the system is thermal energy and not from an electrical source) and three concepts were considered based on the source of heat energy input to the system.

For the vapor absorption refrigeration system three concepts are discussed here alongside their merits and demerits. They are:

i. Propane fired vapor absorption refrigeration.
ii. Combustible waste powered vapor absorption refrigeration.
iii. Solar powered vapor absorption refrigeration

3.2 PROPANE FIRED VAPOUR ABSORPTION REFRIGERATION

A propane-fired vapor absorption refrigerator (VAR) is a refrigeration system powered by heat (from propane combustion) instead of electricity. It operates on the ammonia– water absorption refrigeration cycle, utilizing ammonia (NH_3) as the refrigerant, water

(H_2O) as the absorbent, and hydrogen gas (H_2) to regulate pressure in the evaporator.

This technology dates back to the early 1920s with the Platen Munters invention (one of the earliest absorption refrigerators) which was first produced commercially by Electrolux starting in 1925.

3.2.1 Working Principle & Cycle Components

Some of its Key Components include:

i. Generator (boiler): Heats ammonia–water solution using propane flame.
ii. Separator: Removes water vapor from ammonia vapor.
iii. Condenser: Cools ammonia gas into liquid.

iv. Evaporator: Liquid ammonia evaporates, absorbing heat inside compartment

v. Absorber: Ammonia gas dissolves in water; hydrogen returns to evaporator

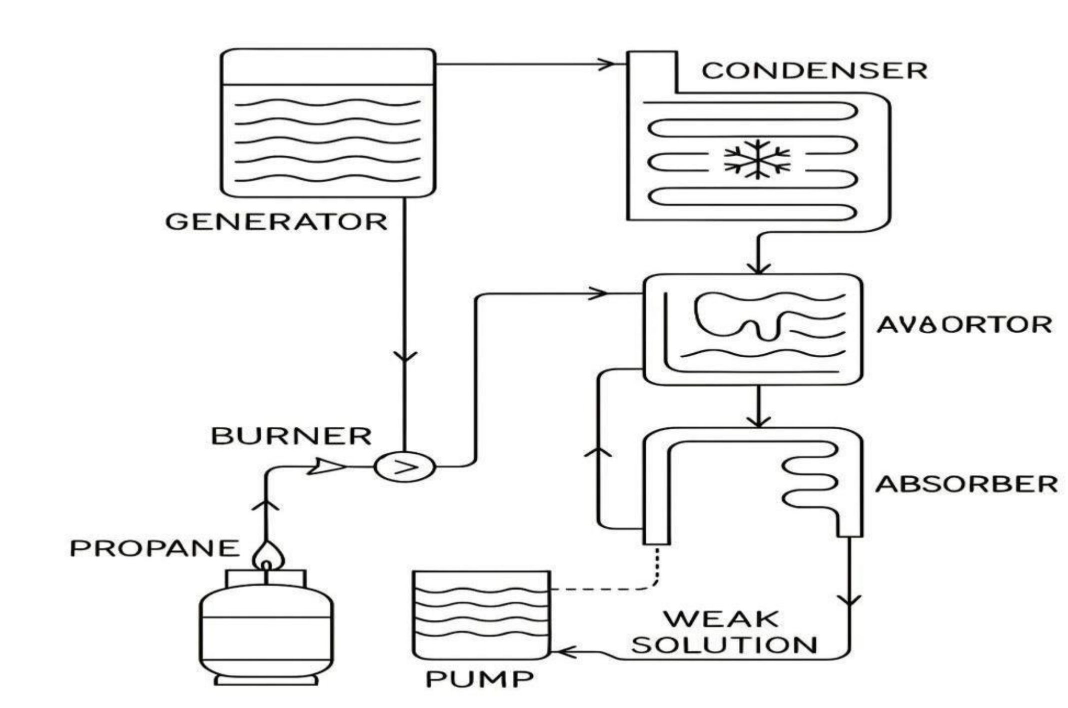

figure 3.1 **A 2D sketch of a propane fired absorption cycle**

3.2.2 Advantages of Propane Fired Var System.

i. **Electricity-free operation**: Ideal for RVs, cabins, and areas off-grid.

ii. **Quiet & low-maintenance**: No moving parts like compressors making it highly reliable.

iii. **Fuel flexibility**: Can be driven by propane, kerosene, solar thermal or waste heat.

iv. **Chemically simple & widely available**: Ammonia is cheap, water is safe and abundant.

v. **Durable**: Fewer mechanical failures over time.

3.2.3 Disadvantages & Risks

a) Low thermodynamic efficiency: COP significantly lower than compressor systems.

b) Slow cooling response: Takes many hours to reach set temperatures when started from warm.

c) Safety concerns: This includes:

i Ammonia toxicity: Toxic at ~300 ppm or above; odor threshold is low (~5 ppm), so early leak detection is possible.

ii Hydrogen gas: Flammable; requires careful sealing.

iii Propane combustion: Produces CO and CO_2—requires proper ventilation.

d) Material limitations: Ammonia corrodes copper alloys; system materials must be carefully selected.

3.2.4 Engineering Applications and Enhancements

Some of the common uses includes:

i. RVs, boats, and caravans
ii. Off-grid homes and remote storage
iii. Vaccine refrigeration in rural clinics

3.3 COMBUSTIBLE WASTE POWERED VAR CYCLE

A Combustible waste refrigerator was designed and fabricated. The combustible vapour absorption refrigerator uses ammonia as its refrigerant, and water is used as the absorbent. The temperatures of the evaporator, generator and condenser were measured and recorded periodically. Combustible solid wastes are organic materials such as wood, paper and fabrics that generate waste heat when they are burnt. The waste heat exhaust into the environment when not reused for useful and economic purpose

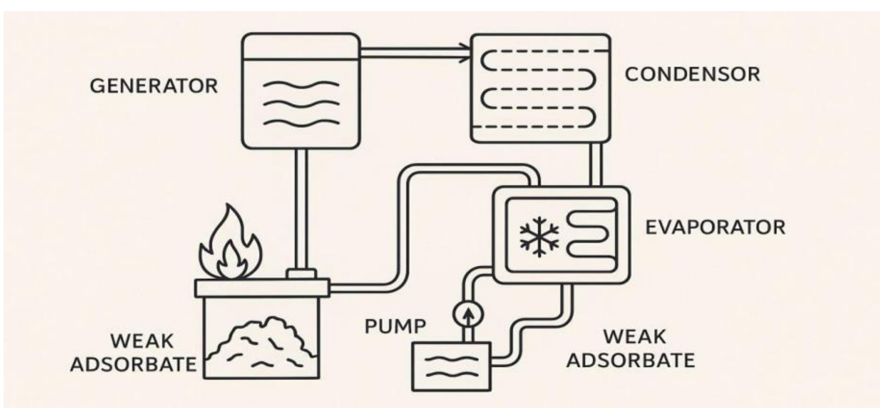

Figure 3.2 **Waste combustion refrigeration cycle**

3.3.1 Advantages of Combustible Waste Powered Var System

i. It is a cheap source of energy (almost free).
ii. Maintenance cost is low and does not require skilled labor.
iii. It is relatively safe.

3.3.2 Disadvantages and Risks:

i. Low heat transfer rate
ii. It is not a clean source of fuel when compared to others.

3.4 SOLAR POWERED VAPOR ADSORPTION REFRIGERATION

An absorption refrigeration system functions similarly to a vapor-compression refrigerator, but with a key difference: the mechanical compressor is replaced by a combination of four components. These include an absorber, which uses a different liquid to absorb the refrigerant vapor to form a solution; a pump that circulates the liquid solution; a generator or boiler that applies heat to separate the vapor from the solution; and an expansion valve that returns the absorbent to the cycle.

One major benefit of this configuration is that it requires significantly less mechanical work to operate; and in some cases, no mechanical input at all if the system uses natural circulation, such as gravity-driven flow in a thermo-siphon. However, this comes at the cost of needing an external heat source to drive the regeneration process (Jordan, 1962).

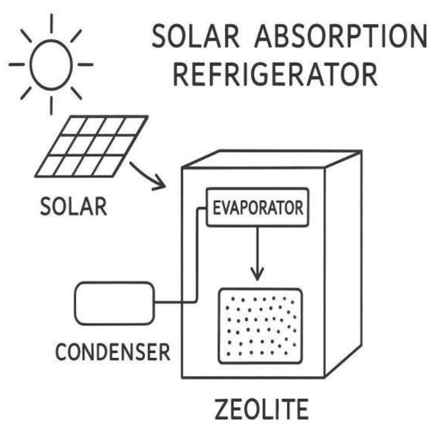

Figure 3.3 **Solar adsorption refrigeration cycle**

3.4.1 Advantages of Solar Powered Vapor Adsorption Refrigeration

i. **Environmental Sustainability**: It utilizes solar energy, a renewable resource, reducing reliance on fossil fuels and lowering greenhouse gas emissions compared to traditional vapor-compression systems.

ii. **Low Operating Costs**: Once installed, the system has minimal operating costs since it primarily uses free solar energy, reducing electricity bills.

iii. **Suitability for Remote Areas**: It is ideal for off-grid locations with abundant sunlight, providing cooling in areas lacking reliable electricity infrastructure.

iv. **Use of Eco-Friendly Refrigerants**: It employs natural refrigerants like water or methanol, avoiding harmful chlorofluorocarbons (CFCs) or hydro fluorocarbons (HFCs) used in conventional systems.

v. **Low Maintenance**: Adsorption systems have fewer moving parts than traditional compressors, leading to reduced wear and tear and lower maintenance requirements.

3.4.2 Disadvantages and Risks

i. **High Initial Cost**: Installation requires expensive components like solar collectors and specialized adsorbers, making the upfront cost significantly higher than conventional systems.

ii. **Intermittent Operation**: Dependent on solar availability, the system may not function effectively at night or during cloudy weather without an auxiliary energy source or storage.

iii. **Lower Efficiency**: Adsorption systems typically have a lower coefficient of performance (COP) compared to vapor-compression systems, resulting in less cooling output per unit of energy input.

iv. **Large Space Requirements**: Requires significant space for solar collectors and system components, which may be impractical in urban settings or small facilities.

v. **Slow Response Time**: The adsorption cycle is slower to start and respond to cooling demands compared to conventional systems, limiting its suitability for rapid or variable cooling needs.

3.4.3 Summary

These points reflect the trade-offs between sustainability and practicality, making solar adsorption systems best suited for specific applications like remote or eco-conscious settings.

3.5 CONCEPT EVALUATION

To make a right selection between all three concepts, an evaluation of the concepts was carried out based on a set of design factors which were considered important in the project.

These include:

i. **Safety**: This is the potential hazards and risks the design may pose to the operator, user and environment. It considers level of pollution, toxicity, e.t c.

ii. **Cost**: This is the careful estimation of the price involved when designing a sustainable refrigeration system. It includes the capital costs associated with the equipment itself, as well as any structural or construction costs. Account for the cost of the refrigerant, as well as the costs of operating and maintaining the system is considered too.

iii. **Maintenance**: It considers accessibility, modularity, and the use of durable, easy-to clean materials to ensure that routine upkeep tasks like cleaning **coils,** checking seals, and replacing filters are straightforward and don't require specialized skills and are also cost effective.

iv. **Thermal input**: It refers to the heat that needs to be removed from the inside of the refrigerator to maintain a low temperature

v. **Complexity of system**: This is the level of technicalities of the design and how it impacts other factors of the system like energy efficiency, reliability, manufacture time and maintainability.

vi. **Performance and Efficiency**: It is a measure of the coefficient of performance (COP), defined as the ratio of heat removed from the cold space to the work input. It refers to how well the machine would deliver its required task when under operation.

3.5.1 Design Factors and Category Weighing

Each of the design factors important to this project are given weights in such a way that the factors considered important for the viability of the project are weighed more and the sum of the weights equals to 1.

This is shown in the table 3.1 below:

S/N	Factors	Weight
1	Cost	0.3
2	Thermal Input	0.15
3	Complexity	0.10
4	Maintenance	0.12
5	Safety	0.25
6	Performance and Efficiency	0.08

Table 3.1 **Category Weighting**

Cost was assigned the highest weight of 0.30 because affordability is a key consideration in sustainable and decentralized cooling systems like solar adsorption. The technology is often targeted at off-grid or low-income regions where budget constraints are real, and keeping overall system cost low is crucial for implementation and scalability. A slightly lower but still high weight of 0.24 was given to Safety, recognizing the need to protect users and technicians from hazards, especially when dealing with pressurized vessels, heat sources, and chemical adsorbents. In any thermodynamic cycle involving heat and fluid flow, safety cannot be compromised, making it a near-equal priority to cost.

The Thermal Power Input was given a weight of 0.15, as this factor significantly influences system efficiency and determines the feasibility of using available solar energy. While it is not as critical as cost or safety, thermal input affects the sustainability and operational effectiveness of the cycle, especially under varying sunlight conditions. Maintenance was assigned a moderate weight of 0.12 because, although the system should ideally be low-maintenance, real-world conditions often involve dust, corrosion, or material fatigue, especially in remote or rural settings. Reducing maintenance frequency and complexity improves reliability and user satisfaction.

Complexity received a weight of 0.10, reflecting a preference for a system that is straightforward to build, operate, and troubleshoot. Since the solar adsorption system may be deployed in locations with limited technical expertise, minimizing complexity is a practical choice. However, the need for performance and function means complexity cannot be entirely avoided. Lastly, Performance and Efficiency was given a weight of 0.08. While these are important engineering targets, the decision to rank them lower stems from the understanding that solar adsorption systems are inherently less efficient than traditional systems. The goal here is not to maximize performance at all costs, but to strike a balance between acceptable efficiency and real-world applicability, especially in areas where conventional refrigeration is not feasible.

This weighting reflects a careful consideration of the practical challenges, user needs, and environmental conditions likely to affect the adoption and success of the Solar Adsorption Refrigeration Cycle.

3.6 MATERIALS FOR SOLAR POWERED VAR

i. **Solar Collectors (Parabolic trough)**: Captures heat energy from the sun which acts as the fuel source by replacing gas or fire.
ii. **Refrigerant (Adsorbate):** The working fluid (water) that gets absorbed by the adsorbent.
iii. **Absorber (Zeolite):** This absorbs the refrigerant vapor back into the absorbent solution and ensures the cycle can continue.
iv. **Condenser:** This cools refrigerant vapor into liquid form and its usually made with copper/aluminum tubing and fins for heat rejection.
v. **Evaporator**: This cooling chamber is where liquid refrigerant evaporates and produces the actual cooling effect.
vi. **Pipes and Valves:** This is used in connecting different components of the system and must be leak-proof and corrosion-resistant to ensure a longer durability and efficiency.

vii. **Insulation Materials:** Prevents heat gain from entering the cooling chamber polyurethane foam or similar insulating materials are commonly used.

3.6.1 Detailed Design

The solar powered vapor absorption refrigerator works by replacing the normal fire or gas source with the energy from the sun. The main idea is simple: sunlight is collected, stored as heat, and used to drive the absorption cycle that produces cooling. The system is designed around a 10litre cold box that keeps food, medicines, or drinks at around 4 - 12 °C in hot ambient conditions of about 35 °C.

At the heart of the system are evacuated tube solar collectors tilted toward the equator to capture maximum sunlight. These collectors heat water in a closed loop, and the hot water is stored in an insulated tank of about 40–60 liters capacity. This tank acts like a thermal battery so that cooling can continue even at night or when the sky is cloudy. Inside the tank, a coil carries heat to the generator of the absorption cycle. This is shown in figure 3.4 below

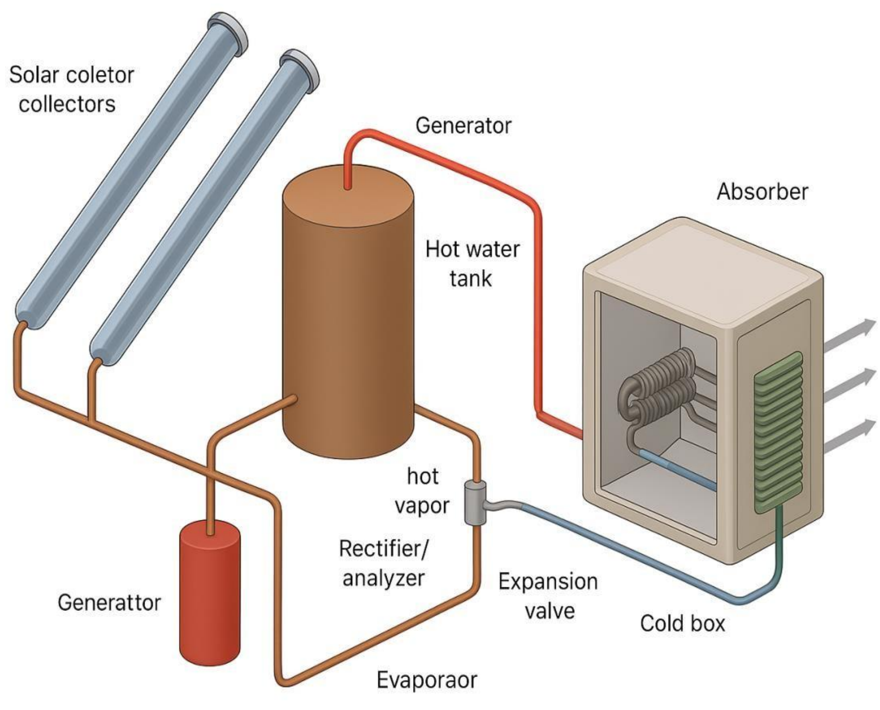

Figure 3.4 **Detailed design of the solar adsorption refrigerator**

The working pair chosen for the refrigeration side is zeolite–water . Zeolite is the refrigerant that evaporates to create cold, while water acts as the absorbent that pulls the zeolite back so the cycle can repeat. The generator, heated by the solar hot water, boils the solution and releases zeolite vapour. Before reaching the condenser, this vapour passes through a rectifier/analyzer section which dries it and ensures only pure Zeolite moves forward. In the condenser, the hot vapour rejects heat to the surrounding air and condenses into liquid. The liquid zeolite then passes through a restriction (capillary or orifice) and enters the evaporator at low pressure. Inside the evaporator coil, the zeolite evaporates again, absorbing heat from the contents of the fridge, which produces the cooling effect. The vapour then flows into the absorber, where it is reabsorbed into the weak water solution, completing the cycle.

A solution heat exchanger between the rich and weak solutions improves efficiency by recovering heat, and a small pump or gravity flow circulates the solution back to the generator.

The cold box itself is built with food-grade stainless steel or HDPE liner, surrounded by at least 50 mm of polyurethane foam insulation to trap the cold. A tight magnetic or silicone gasket on the lid reduces leakage of cool air. The absorber and condenser coils are air-cooled, preferably with fins to enlarge surface area. Small DC fans powered by a mini PV panel and battery can assist during very hot days. All zeolite side piping and vessels are made of carbon steel or stainless steel (never copper, since zeolite attacks it). Safety features include a pressure relief valve, a high-pressure cut-out switch, and an ammonia detector.

In terms of energy balance, the 10-litre box needs about 0.4–0.45 kWh of cooling per day under real use. With a thermal COP of about 0.35, the generator must be supplied with around 1.3 kWh of heat daily. A 1.5–2.0 m^2 evacuated tube collector array is sufficient to deliver this amount with margin, given local solar insolation of about 5 $kWh/m^2/day$. The insulated water tank stores the heat so that about two-thirds of the cooling can be covered during night hours.

Control is straightforward: a differential thermostat runs the solar pump whenever the collector is hotter than the tank by about 8 K. A fridge thermostat opens a hot-water valve to the generator whenever box temperature rises above 6 °C, and closes it when it falls below 2–3 °C. Fans on the absorber or condenser cut in only when those coils exceed about 42 °C.

Altogether, the system is compact, quiet, and safe. It consumes almost no electricity except for small pumps and fans, which can be powered by a modest solar panel and battery. The heavy lifting is done by free sunlight stored as heat. The design swaps the dependence on fuel or firewood for a clean, renewable source, and makes the refrigerator ideal for off-grid areas, health posts, and rural homes

3.6.2 DECISION MATRIX

The decision matrix applied is shown in the table below:

S/N	Factors	Weighting	Concept 1		Concept 2		Concept 3	
			score	Weighted score	score	Weighted score	score	Weighted score
1	Cost	0.3	2.0	0.6	6.0	1.8	5.6	1.68
2	Thermal Input	0.15	5.0	0.75	4.0	0.6	3.5	0.525
3	Complexity	0.10	3.0	0.3	6.5	0.65	7.0	0.7
4	Maintenance	0.12	2.5	0.3	3.0	0.36	5.5	0.66
5	Safety	0.25	2.2	0.55	4.5	1.125	4.5	1.125
6	Performance and Efficiency	0.08	2.0	0.16	3.0	0.24	5.2	0.416
Total		1.00		2.66		4.78		5.11

Table 3.2 **Decision matrix**

The solar-powered vapor absorption refrigerator is the most suitable and better choice due to its environmental sustainability, low operating costs, safety, reliability in sunny regions, and alignment with renewable energy trends. Unlike propane-fired systems, it avoids greenhouse gas emissions and fuel dependency. Compared to combustible waste-powered systems, it eliminates pollution, safety risks, and inconsistent fuel quality issues. While it requires a higher initial investment and sufficient sunlight these challenges are manageable with modern Technology and are outweighed by long term benefits, making it the preferred choice for eco-friendly, cost-effective and safe refrigeration in especially remote or sunny regions.

3.6.3 Core Equations (Zeolite–Water Adsorption)

Formulas:

Box conduction heat flow:

$Q_{box} = U \times A \times \Delta T$

Daily baseline cooling energy:

$E_{cool,\ base} = Q_{box} \times 24\text{hours}$

Adjusted daily cooling (with margin):

$E_{cool} = E_{cool,base} \times (1 + \text{margin})$

Water mass evaporated per day:

$m_{water} = E_{cool}$ (in kJ) ÷ hfg Zeolite
mass required:

$m_{zeolite} = m_{water} \div \Delta W$ Solar
thermal input required:

Q_{in} solar = E_{cool} ÷ COP thermal

Collector useful energy per square meter:

Useful per $m^2 = G_{daily} \times$ efficiency Collector
area:

$A_{collector} = Q_{in}$ solar ÷ Useful per m_2

Final $A_{collector} = A_{collector} \times$ margin factor Total heat rejected per day:

$Q_{reject} = Q_{in}$ solar + E_{cool}

Average rejected power:

P_{reject} average = ($Q_{reject} \times 1000$) ÷ 24 Heat exchanger sizing:

UA = P_{reject} average ÷ΔTlm

Evaporator surface guideline:

$A_{evap} \approx 0.15$ to $0.25\ m^2$ for a 10 L fridge

Sample Calculation for 10L Fridge

Given values

$U = 0.5\ W/m^2K$

$A = 0.618\ m^2$

$T_{outside} = 35$ °C, $T_{inside} = 4$ °C → $\Delta T = 31$ K

Usage margin = 50% hfg = 2440 kJ/kg

$\Delta W = 0.12 kg_{water}$ per $kg_{zeolite}$ $COP_{thermal} = 0.25$

$G_{daily} = 5.0\ kWh/m^2/day$

Efficiency = 0.33

Margin factor = 1.6

 Step 1 – Heat leak through box

$Q_{box} = 0.5 \times 0.618 \times 31 = 9.58$ W

$E_{cool,base} = 9.58 \times 24 = 230$ Wh/day = 0.230 kWh/day Add usage margin:

$E_{cool} = 0.230 \times 1.5 = 0.345$ kWh/day

Design round-up: $E_{cool\ design} = 0.45$ kWh/day = 1620 kJ/day

4 Step 2 – Water evaporated $m_{water} = 1620 \div 2440 = 0.664$ kg/day 5 Step 3 – Zeolite mass $m_{zeolite} = 0.664 \div 0.12 = 5.53$ kg

(Choose ~6–7 kg, split into 2 beds of 3–4 kg each)

6 Step 4 – Solar thermal input

$Q_{in\ solar} = 0.45 \div 0.25 = 1.8$ kWh/day

= 6.48 MJ/day

7 Step 5 – Collector area

Useful per $m^2 = 5.0 \times 0.33 = 1.65$ kWh/m²/day

$A_{collector} = 1.8 \div 1.65 = 1.09$ m²

Final $A_{collector} = 1.09 \times 1.6 = 1.75$ m²

(Choose ~2.0 m² high-temp solar collector)

8 Step 6 – Heat rejection sizing

$Q_{reject} = 1.8 + 0.45 = 2.25$ kWh/day

$P_{reject,\ average} = (2250$ Wh $\div$ 24 h$) = 93.8$ W

$UA = 93.8 \div 10 \approx 9.4$ W/K

9 Step 7 – Evaporator area

$A_{evap} \approx 0.20$ m²

3.6.4 Result Summary

i Cooling load = 0.45 kWh/day (1620 kJ/day)
ii Water evaporated = 0.664 kg/day
iii Zeolite = 6–7 kg total
iv Solar input = 1.8 kWh/day
v Collector area = ~2.0 m²
vi Heat rejection = ~94 W (UA ~9.4 W/K)
vii Evaporator area = ~0.20 m²

3.6.5 Geometric Modeling of Components for Zeolite-Water VARs

This stage was carried out by the use of CAD software. The component parts of the system to be fabricated were first modeled to size to give us the view of how they should look like in reality. These components include:

i. The Evaporated Space/Refrigerator Body

The evaporated space measures 0.525m x 0.505 m 0.52m given it a maximum volumetric capacity of 0.0137865m³. The refrigerator body is shown in the figure below:

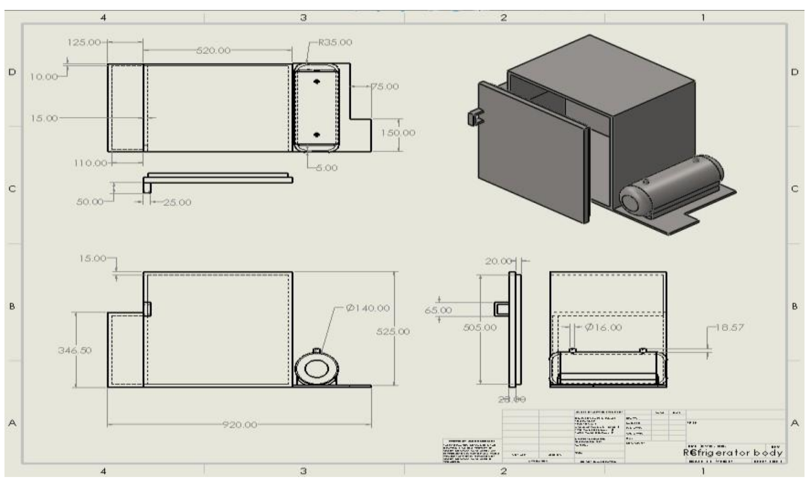

Figure 3.5 **Refrigerator Body**

It is the compartment in which evaporation of refrigerant and cooling occurs

ii. Solar Collector

The parabolic trough collector is the most critical external component and serves as the heat source. It is essentially a curved reflective surface that focuses sunlight onto a receiver tube containing the zeolite bed. It is shown in the figure below

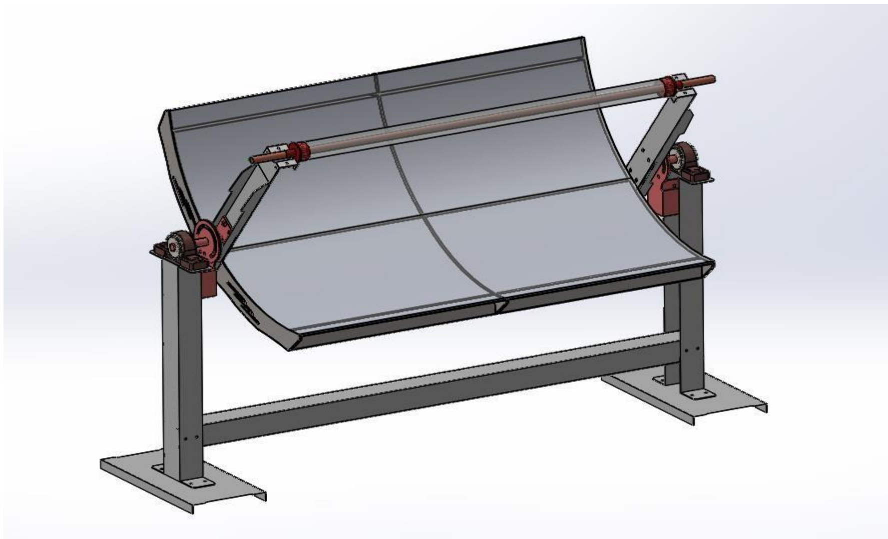

Figure 3.6 **Parabolic Trough Collector**

During the day, concentrated solar energy heats the zeolite to high temperatures, driving off the water vapor it had adsorbed overnight. This vapor then travels to the condenser to complete the cycle. The parabolic trough design is highly efficient, as it maximizes solar energy capture compared to flat-plate collectors, making the system more reliable in rural and off-grid settings**.** It collects sunlight energy, from the sun to power our refrigerator.

iii. The Condenser

Having a dimension of 0.364m x 0.075m x 0.09m, the condenser is used to cooling the water vapor released from the zeolite during the day and turns it back into liquid The condenser is shown in the figure 3.7 below

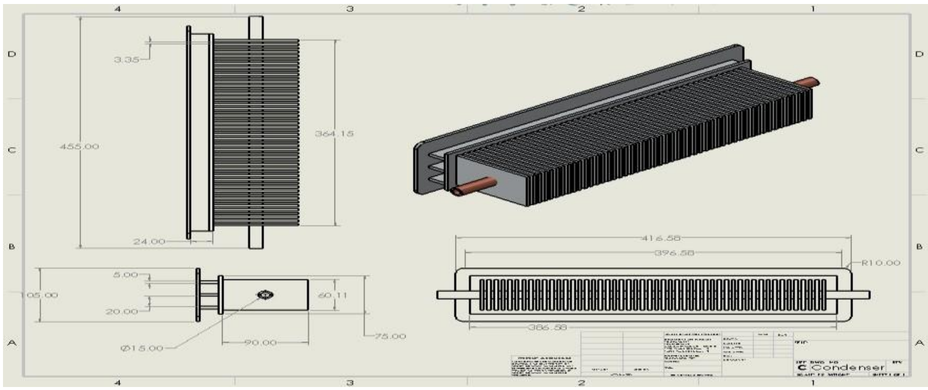

Figure 3.7 **The Condenser**

This liquid is then stored and later sent to the evaporator at night to produce cooling. Without the condenser, the cycle cannot be completed and efficiency drops.

iv. The Evaporator

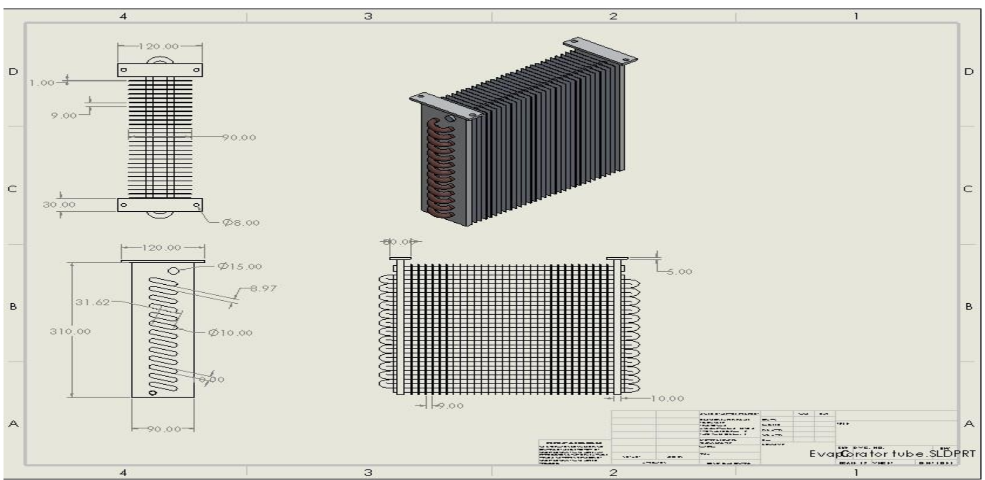

Figure 3.8 ***The Evaporator***

The evaporator is the cold part of the fridge. Here, the liquid water turns into vapor by absorbing heat, which makes the inside cool. It is shown in the figure 3.8 above

3.6.6 Assembly of the Refrigerator

The solar zeolite refrigerator is composed of four main parts: the refrigerator body, the condenser, the evaporator, and the parabolic trough collector. These elements work together in a closed cycle to provide sustainable cooling using only solar heat as the energy source.

The refrigerator body is a well-insulated compartment, designed to hold approximately 10 liters of perishable goods or medicines. Its main function is to maintain a low internal temperature for as long as possible by minimizing heat gains from the external environment. The insulation is typically polyurethane foam or similar low-conductivity material. Within this compartment, the evaporator coil is installed to ensure direct heat absorption from the stored contents. The body acts as the user interface of the system (where cooling is experienced). It is shown in the figure below

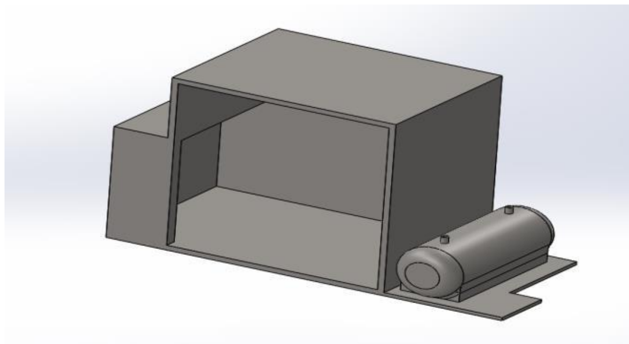

Figure 3.9 **Refrigerator Body**

The condenser is mounted outside the refrigerator box, generally at the back or side, where it can dissipate heat freely to the surrounding air. Constructed from copper or aluminum tubing with extended fins, the condenser cools the vapor released from the zeolite bed and converts it into liquid water. This liquid then flows down into a small receiver before moving toward the evaporator. The efficiency of the condenser directly influences the rate of cooling and the overall performance of the system. It is shown in the figure 3.10 below

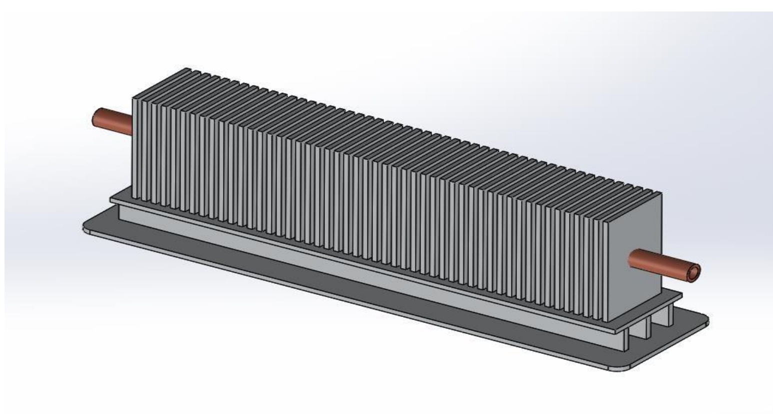

Figure 3.10 **The Condenser**

The evaporator, placed inside the refrigerator body, is the actual cooling element. It is usually designed as a coil or flat plate to maximize contact with the air inside the fridge. At night, when the zeolite cools and starts reabsorbing vapor, liquid water from the receiver enters the evaporator. The low pressure in the system causes the water to evaporate, and in doing so, it absorbs heat from the stored items. It is shown in the figure 3.11 below

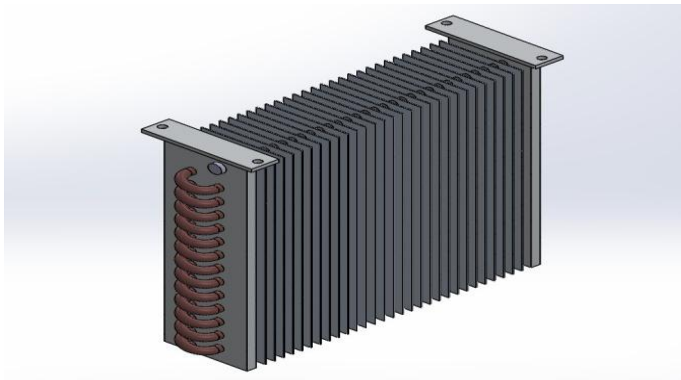

Figure 3.11 **The Evaporator**

This is what produces the cooling effect that keeps the fridge interior cold.

Together, these components form a closed adsorption refrigeration cycle: Parabolic trough collector with zeolite bed → Condenser → Receiver → Evaporator → back to zeolite bed.

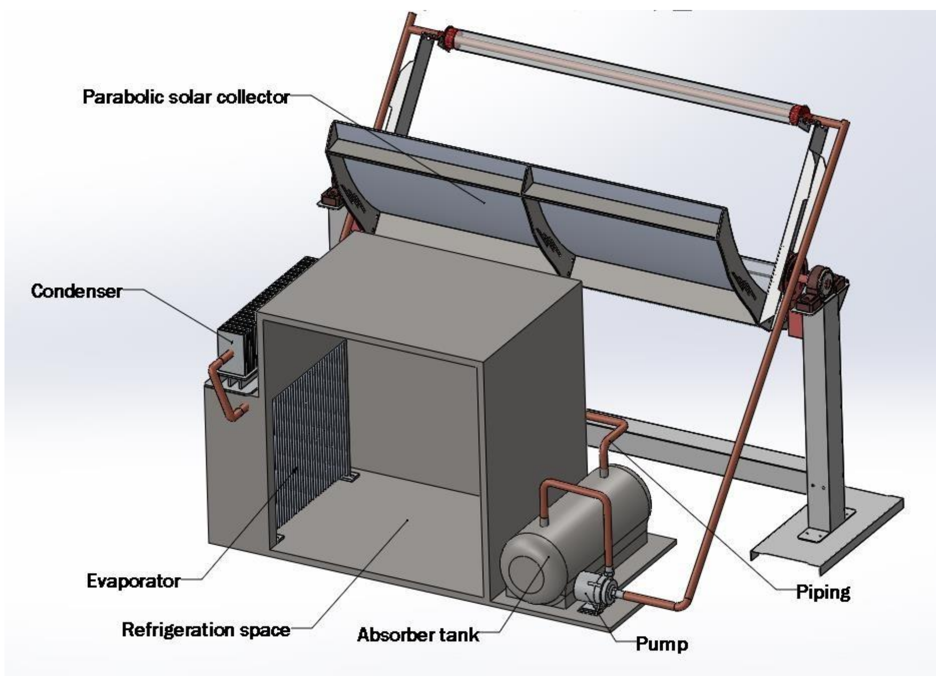

Figure 3.12 **Assembled Solar Adsorption Refrigerator**

The system requires no electricity or mechanical compressor, relying solely on solar thermal energy and the natural adsorption properties of zeolite. The assembled refrigerator is shown in the figure 3.12 and 3.13

Figure 3.13 **Side view of assembled Solar Adsorption Refrigerator**

The stepwise procedure of this refrigerant flow is shown in figure 3.14 below:

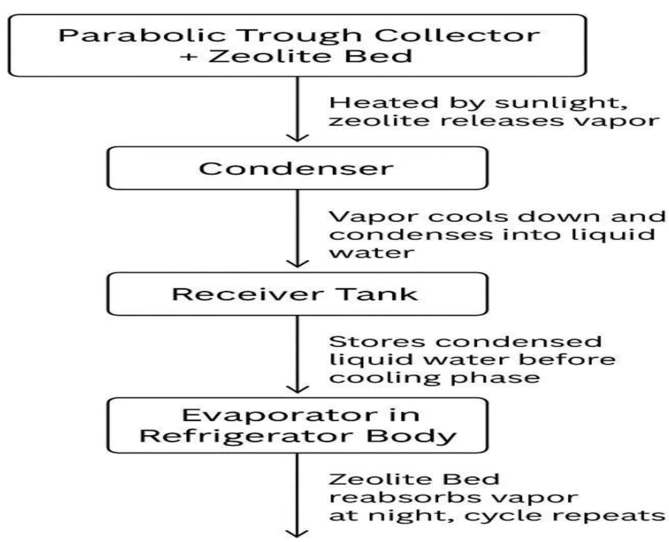

Figure 3.14 **Refrigerant Flow**

3.6.7 Bill of Measurement of the Solar Adsorption Refrigerator

The table 3.3 below shows the cost implications of the materials and processes used in carrying out the project.

Item	Quantity	Unit cost	Total cost
Frame	bulk	80,000	80,000
Bearings	2	8000	16,000
Gears	2	5000	10,000
Base plate	2	5000	10,000
Parabolic trough with zeolite	bulk	80,000	80,000
Evaporator with copper tubing	bulk	80,000	80,000
Refrigerator	1	210,000	210,000
Absorption tank	1	10,000	10,000
Solar absorber/glacier + heater enhancer	bulk	1	140000
Pump	1	40,000	40,000
Condenser	1	40,000	40,000
Bracing process	sum	20,000	20,000
Miscellaneous	sum	50,000	50,000
Labor	sum	220,000	220,000
TOTAL			**1,006,000**

Table 3.3 **Bill of Material**

3.6.8 Fabrication Process of Vapor Absorption Refrigerator

Figure 3.15 below shows the students carrying out the fabrication process in the workshop

Figure 3.15 **Fabrication process**

These are the processes or Activities carried out during the fabrication of our refrigerator

i. **Cutting & Shaping**: Cut metal sheets and pipes to required sizes for the frame, condenser, and evaporator.
ii. **Welding**: Join the structural frame, supports, and brackets.
iii. **Drilling**: Create holes for mounting components, piping, and fasteners.
iv. **Bending & Forming**: Bend copper tubes for the condenser and evaporator coils.
v. **Grinding & Finishing**: Smooth welded joints and sharp edges.
vi. **Brazing/Soldering**: Seal copper tube joints in condenser and evaporator.
vii. **Surface Treatment**: Apply anti-rust coating or paint on steel parts.
viii. **Insulation Work**: Fill fridge body walls with polyurethane foam and install inner lining.
ix. **Assembly & Fitting**: Mount collector, zeolite bed, condenser, evaporator, and connect with tubing.
x. **Leak Testing**: Check all joints for air-tightness before charging with zeolite and water.

The actual final product is shown in the figure 3.16 below

Figure 3.16 **final product**

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

The results obtained from the experimental investigation provide important insights into how variations in temperature, pressure, and solar energy input influence the performance of the solar adsorption refrigeration system using the zeolite–water working pair. This section discusses the findings in relation to key performance parameters, including temperature distribution across the major components, system pressures, solar collector response, and the overall coefficient of performance (COP). The system was operated for a period of three hours under natural solar radiation, with supplementary heating applied in the generator to achieve the required desorption temperature. Readings were recorded using Resistance Temperature Detectors (RTDs) at the evaporator, condenser, generator, absorber, solar collector, and the surrounding ambient environment, while pressure gauges monitored both the low- and high-pressure sides of the system. These measurements were used to evaluate the thermal behavior, energy transfer, and operational stability of the cycle during adsorption and desorption phases. Table 4.1 below shows the result obtained

SYSTEM PARAMETER	RESULT	
	Temp	**PRESSURE**
Evaporator temp	18^{o}C	2KPa
Condenser temp	29^{o}C	7.4KPa
Ambient temp	25^{o}C	101.325KPa
Generator temp	115^{o}C	7.4KPa
Adsorber temp	48^{o}C	2KPa
Solar collector temp	52^{o}C	____
Pump mass flow rate	0.001108Kg/s	_____
Solar radiation (mean)	4.5KWh/m^2	_____
COP Calculated with corresponding enthalpy values= 0.66		

Table 4.1 Result Obtained

Key thermodynamic phenomena such as vapor generation in the evaporator, condensation in the condenser, and adsorption–desorption dynamics in the zeolite bed were analyzed to understand their contributions to system efficiency. The interplay between temperature and pressure variations was carefully examined to determine how these parameters affected the rate of heat transfer and refrigerant circulation within the closed loop.

The discussion also addresses the trade-offs observed during operation, such as the influence of solar intensity fluctuations and thermal losses on overall system performance. The calculated

COP of 0.66, derived from corresponding enthalpy values, was used to assess the system's efficiency relative to similar solar adsorption refrigeration prototypes.

This section further explores the implications of these findings for real-world applications, providing valuable insights into the optimization of adsorption-based refrigeration systems for off-grid and energy-efficient cooling. Recommendations are also made regarding improvements in insulation, adsorbent material configuration, and heat recovery strategies to enhance future system performance.

4.1.1 Temperature and Pressure Variation During Operation

During system operation, the temperature and pressure readings at various components revealed the characteristic thermodynamic behavior of the solar adsorption refrigeration cycle. The evaporator operated at about 18 °C and a low pressure of 2 kPa, indicating the region where the refrigerant evaporated by absorbing heat from the cooling chamber. This low-pressure condition is essential for effective evaporation and directly corresponds to the adsorption phase occurring simultaneously in the adsorber. At this stage, the adsorbent bed maintained a temperature of about 48 °C and a pressure of 2 kPa, which facilitated the adsorption of refrigerant vapor, released from the evaporator. The exothermic nature of adsorption caused a slight temperature rise within the adsorber even though it remained under low pressure.

The condenser and generator formed the high-pressure side of the system, both recording pressures of about 7.4 kPa. In the condenser, the refrigerant vapor released from the generator condensed at approximately 29 °C, releasing latent heat to the surroundings. The relatively low condenser temperature compared to the generator temperature indicated efficient condensation and proper maintenance of the pressure differential between the two sides of the system. The generator, on the other hand, reached a maximum temperature of about 115 °C when the solar collector and gas burner reheater worked in combination. At this elevated temperature, the adsorbent released the refrigerant vapour—a process known as desorption—thereby establishing the high-pressure phase of the cycle.

The solar collector attained a maximum temperature of around 52 °C, while the ambient temperature was about 25 °C, confirming effective but partial solar contribution to the heating of the generator. This temperature variation across the components reflects the alternating nature of the adsorption refrigeration process: during desorption, heat supplied to the generator increases system pressure and drives the refrigerant to the condenser; during adsorption, the removal of heat from the adsorber lowers the pressure, drawing vapor from the evaporator. The observed temperature and pressure distributions therefore illustrate the proper thermodynamic transitions of evaporation, condensation, desorption, and adsorption within the cycle, validating the overall system functionality.

4.1.2 Performance of the Solar Collector

The performance of the solar collector played a crucial role in determining the overall effectiveness of the adsorption refrigeration system. During operation, the collector reached a maximum temperature of approximately 52 °C under an average solar radiation intensity of 4.5 kWh/m^2 and a working fluid mass flow rate of 0.001108 kg/s. These conditions indicate that the collector was able to effectively absorb solar energy and transfer it to the heat transfer fluid circulating through the system. However, while the solar collector provided a steady temperature rise, it was not sufficient on its own to achieve the high desorption temperature required for the generator to function optimally. As a result, a supplementary gas burner was employed as a reheater to elevate the generator temperature to about 115 °C, ensuring complete desorption of the refrigerant from the adsorbent.

This combined heating approach highlights that the solar collector provided a substantial portion of the required thermal input, but its output temperature was limited by factors such as collector efficiency, environmental losses, and system design. The efficiency of a solar collector generally depends on its ability to minimize heat losses through conduction, convection, and radiation. In this setup, part of the absorbed energy was lost to the environment due to imperfect insulation and possibly suboptimal orientation or tilt of the collector with respect to the sun. These losses reduced the collector's thermal efficiency and limited the extent of solar contribution to the generator heating process.

The temperature profile recorded during the test suggested that the collector temperature rose gradually with solar radiation intensity and stabilized once thermal equilibrium was reached between the absorber plate and the circulating fluid. The steady flow rate of 0.001108 kg/s helped maintain consistent heat transfer, preventing excessive temperature fluctuation within the collector. Nevertheless, the moderate outlet temperature of 52 °C indicated that only partial desorption could be achieved under solar heating alone.

The solar collector contributed significantly to the system's energy input, reducing dependence on the auxiliary burner. However, improvements such as increasing the collector surface area, enhancing thermal insulation, optimizing the flow path for better heat absorption, and incorporating a solar tracking mechanism could substantially increase collector temperature and efficiency. By achieving higher solar outlet temperatures, future versions of the system could rely more heavily on renewable solar energy, reducing fuel use for reheating and improving the overall sustainability of the refrigeration process.

4.1.3 System Pressure Behavior and Refrigerant Circulation

The pressure behavior of the system provided important insight into how effectively the refrigerant circulated through the adsorption refrigeration cycle. Throughout operation, the system maintained two distinct pressure zones: the high-pressure side, which included the generator and condenser at approximately 7.4 kPa, and the low-pressure side, consisting of the adsorber and evaporator at about 2 kPa. This difference in pressure (roughly 5.4 kPa) is essential for driving the natural flow of refrigerant between the components without the need for a mechanical compressor.

During the desorption phase, when the generator was heated to around 115 °C, the refrigerant was released from the adsorbent as vapor under high pressure. This vapor moved toward the condenser, where it lost latent heat and condensed into liquid form. The pressure remained relatively stable at 7.4 kPa during this process, confirming that the system maintained a strong high-pressure region capable of supporting effective condensation. When the liquid refrigerant later expanded or migrated toward the evaporator, it entered the low-pressure region maintained by the adsorber.

In the adsorption phase, the adsorber's pressure of 2 kPa created a strong driving force for vapor to flow from the evaporator. At this stage, the evaporator absorbed heat from the surroundings, causing the refrigerant to evaporate and produce the cooling effect. The vapor produced at low pressure was then adsorbed by the adsorbent material, maintaining system stability. This continuous exchange between high- and low-pressure regions is what sustains refrigerant circulation and allows the cycle to operate without moving mechanical parts.

The stability of the pressure difference throughout the 3-hour operation indicated that the system was functioning properly, with consistent adsorption and desorption occurring at their respective pressure ranges. However, minor fluctuations may have occurred due to variations in solar intensity or non-uniform heating within the generator. These small deviations could momentarily affect refrigerant flow or adsorption capacity but did not appear to destabilize the system significantly. In future designs, improved sealing, better control of the heating and cooling rates, and optimization of adsorbent bed geometry could further enhance pressure stability and, consequently, improve refrigerant circulation and cooling performance.

4.1.4 Analysis of Enthalpy Values and Energy Balance

The analysis of enthalpy values and the system's overall energy balance provides a clear understanding of how heat was absorbed, transferred, and rejected throughout the solar adsorption refrigeration cycle. The energy interactions within the system can be explained through the fundamental thermodynamic processes of desorption, condensation, evaporation, and adsorption, each associated with a corresponding enthalpy change.

In the generator, the adsorbent–refrigerant pair absorbed thermal energy supplied by the solar collector and the auxiliary gas burner. This input energy, denoted as Qgen, caused desorption.

The heat supplied to the generator can be expressed as:

$$Qgen=\dot{m}\,(h2-h1)$$

Where $\dot{m}$ is the refrigerant mass flow rate, and h2 and h1 are the enthalpy values before and after desorption respectively. This stage represents the main energy input to the system.

The high-pressure refrigerant vapor produced in the generator moved into the condenser, where it rejected heat to the surroundings and condensed into liquid form. The amount of heat rejected in the condenser is represented by

$$Qcond=\dot{m}\,(h2-h3)$$

This process did not contribute to the cooling effect but was necessary for completing the refrigerant cycle. The condensed liquid then flowed toward the evaporator, where it experienced a significant drop in pressure.

Within the evaporator, the refrigerant absorbed heat from the refrigerated space and evaporated, providing the desired cooling effect. The heat absorbed here is the useful cooling output of the system and is expressed as

$$Qevap=\dot{m}\,(h4-h3)$$

The refrigerant vapor generated in the evaporator was then drawn toward the adsorber, where it was reabsorbed by the adsorbent material, releasing the adsorption heat Qads to the surroundings.

From the result data obtained, the system's overall coefficient of performance (COP) was calculated to be 0.66. This means that for every 1 kJ of heat supplied to the generator, the system was able to produce about 0.66 kJ of useful cooling effect in the evaporator. The remaining portion of the input energy was dissipated as heat losses through the condenser, adsorber, and other components. The energy balance of the system can therefore be represented as: $Qgen=Qevap+Qcond+Qads+Qloss$

The relatively moderate COP value obtained suggests that while the cycle operated effectively, a considerable amount of the supplied heat was not converted into useful cooling. These losses could have resulted from incomplete desorption due to non-uniform heating, heat leakages in the generator and collector, or limited thermal conductivity within the adsorbent bed.

The enthalpy analysis confirms that the energy flow within the system followed the expected thermodynamic pattern of an adsorption refrigeration cycle. The generator served as the main energy input component, the evaporator provided the cooling effect, and the condenser–adsorber pair rejected the residual heat to close the cycle. This energy relationship forms the basis for the COP value and validates the performance behavior observed during system operation.

4.1.5 Coefficient of Performance (Cop) Evaluation

In the testing of the solar adsorption refrigeration project, we measured the generator, condenser, and evaporator temperatures and pressures. These values were converted into refrigerant enthalpies using standard steam/water saturation tables with a small superheat correction applied to the generator vapor. The enthalpy values obtained were:

10 Saturated liquid at condenser conditions (41 °C): h_f = 171.71kJ/kg
11 Saturated vapor at evaporator conditions (18 °C): h_g = 2533.80 kJ/kg
12 Generator vapor (superheated at 115 °C, 7.4 kPa): $h_{gen} \approx$ 2715.90kJ/kg From these values, the cooling effect per kg refrigerant was:

$$Q_{evap}=h_g - h_f=2362.09 \text{ kJ/kg}$$ The

generator enthalpy increment was:

$$Q_{gen,refrig}= h_{gen} - h_f = 2544.19 \text{ kJ/kg}$$

During operation, the gas burner provided additional heat to raise the generator/adsorbent bed temperature. This extra contribution corresponded to an enthalpy of: Q_{extras} = 1034.73 kJ/kg

The circulating pump used in the experiment had a fixed mass flow rate **of** 0.001108 kg/s (≈3.99 kg/h). With this flow rate, the solar collector supplied the refrigerant enthalpy increment, while the burner supplied the extras. The total generator heat input was therefore: $Q_{gen,total} = Q_{gen,refrig} + Q_{extras}$=3578.92 kJ/kg

At the chosen mass flow, this corresponded to a total generator heat rate of 3.97 kW, while the cooling power produced was 2.62 kW. The resulting coefficient of performance was:

$$COP = \frac{2.62}{3.97} = 0.66$$

Literature values for solar adsorption refrigeration systems typically range between 0.2–0.6, depending on adsorbent–refrigerant pair and operating conditions. The achieved COP of 0.66 is therefore competitive and demonstrates good system performance, though further improvements in insulation and adsorbent efficiency could reduce the burner's contribution and raise efficiency further.

4.1.6 Effect of Component Temperatures on System Efficiency

During the test, the temperatures of the generator, condenser, and evaporator were found to have a direct influence on the adsorption–desorption cycle and ultimately on the system's COP. The generator temperature is the most critical factor because it provides the driving force for desorption. In our case, heating the generator to about 115 °C allowed refrigerant vapor to be released from the adsorbent bed. However, this process also required significant additional heat to raise the temperature of the adsorbent and its metal matrix, which was supplied by the burner.

That extra heat demand was quantified as 1034.73 kJ/kg, and it represents the main penalty that reduced the COP to 0.66. This shows that while higher generator temperatures are necessary to achieve desorption, they also increase the sensible heat load, meaning efficiency depends on finding a balance where desorption occurs effectively without excessive heating.

The condenser temperature, measured at around 41 °C, set the high-side pressure of the system. When condenser temperature rises, the generator must reach even higher temperatures to maintain refrigerant flow, which further increases the heat input requirement and lowers efficiency. Keeping the condenser temperature as low as possible is therefore essential, since it reduces the burden on the generator and allows desorption to occur at lower energy cost. In practice, this means that condenser performance is strongly tied to ambient conditions and the effectiveness of heat rejection.

The evaporator temperature, measured at about 18 °C, determined the cooling capacity of the system. Lower evaporator temperatures increase the enthalpy difference between vapor and liquid, which enhances the cooling effect per kilogram of refrigerant. However, if the evaporator is driven too cold, adsorption rates slow down and cycle times lengthen, which can reduce overall throughput. The evaporator therefore needs to operate at a temperature that balances cooling capacity with adsorption kinetics, ensuring that refrigerant uptake remains efficient.

Taken together, these observations show that the generator is the limiting component in the system. The large sensible heat requirement of the adsorbent bed dominated the energy balance and forced reliance on burner input to maintain operation. Improving generator design, insulation, and internal heat transfer would reduce this penalty and move the COP closer to its theoretical maximum. At the same time, maintaining low condenser temperatures and optimizing evaporator operation would further enhance efficiency, but the generator remains the critical bottleneck that must be addressed for significant performance gains.

4.2 DISCUSSION

In this solar adsorption refrigeration system, the generator reached the highest temperature during operation, rising to about 115 °C as heating progressed. The condenser stabilized at approximately 41 °C, which was higher than the ambient temperature of 27 °C, while the evaporator maintained a temperature near 18 °C to provide the cooling effect. Over the course of the test, the refrigerated space showed a measurable drop in temperature, confirming that the adsorption–desorption cycle was functioning as intended under the combined influence of solar input and auxiliary burner heating.

The energy balance based on measured enthalpies indicated that the cooling effect per kilogram of refrigerant was 2362.09 kJ, while the generator required a total of 3578.92 kJ/kg. The difference, amounting to 1034.73 kJ/kg, was supplied by the gas burner to cover the sensible heating of the adsorbent bed and system losses. With the pump operating at a fixed mass flow rate of 0.001108 kg/s, the cooling power achieved was 2.62 kW, and the total generator input was 3.97 kW. This yielded a coefficient of performance (COP) of 0.66.

Although this COP is lower than the theoretical refrigerant-only value, it is consistent with the performance range reported for solar adsorption refrigeration systems, which typically fall between 0.2 and 0.6 depending on adsorbent–refrigerant pair and operating conditions. Achieving 0.66 therefore demonstrates promising efficiency for a single-bed solar adsorption cycle, especially given the unavoidable thermal mass and heat losses in the generator. With respect to these results, the feasibility of the solar adsorption refrigeration system is validated, and further improvements in insulation, adsorbent configuration, and heat transfer could reduce the burner's contribution and raise the COP closer to its theoretical maximum.

4.3 CHALLENGES

The development of the solar adsorption refrigeration system was met with foundational challenges, beginning with the procurement of zeolite, which proved difficult due to its relative scarcity and limited local availability. This constraint delayed early progress and required extensive sourcing efforts. Additionally, understanding the underlying principles of adsorption refrigeration demanded significant research, as the thermodynamic interactions between the zeolite–water pair and the solar-driven cycle are complex and less commonly applied in conventional cooling systems. Translating this theoretical understanding into a practical framework was equally demanding, as finalizing a clear conceptual design, detailed system layout, and precise specifications required iterative refinement and careful alignment of component functions to ensure operational feasibility and performance reliability.

Several operational challenges were encountered during the experimental investigation of the solar adsorption refrigeration system. One of the most significant issues was the inability of the solar collector alone to raise the generator temperature to the desired level for effective desorption. Although the collector reached a peak temperature of approximately 52 °C under average solar radiation of 4.5 kWh/m^2, this was insufficient to drive the zeolite–water pair to release refrigerant vapor. Consequently, supplementary heating was required, and a gas burner was employed to elevate the generator temperature to about 115 °C. This reliance on auxiliary heating introduced additional energy input that reduced the overall sustainability and efficiency of the system.

Another challenge was the extended time required for the generator to reach operational temperature. Even with the burner in use, the system exhibited a slow thermal response, often taking over two hours to heat the adsorbent bed sufficiently. This delay was primarily due to the high thermal mass of the zeolite and its metal container, which demanded substantial sensible heat before desorption could begin. The long startup time not only hindered the performance evaluation but also highlighted the need for improved heat transfer mechanisms within the generator.

Thermal losses throughout the system further complicated performance. Imperfect insulation around the generator, piping, and solar collector led to significant heat dissipation to the surroundings. These losses diminished the effective energy available for desorption and contributed to the moderate coefficient of performance (COP) observed. Additionally, the fixed mass flow rate of the circulating pump limited the flexibility of heat transfer control, making it difficult to optimize the thermal balance between components during dynamic solar conditions.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSION

This project focused on the design, fabrication, and performance analysis of a solar-powered adsorption refrigeration system aimed at providing affordable, sustainable, and eco-friendly cooling, particularly for off-grid and electricity-deficient regions. The system was successfully designed and tested to demonstrate its functionality. The performance evaluation revealed that, although the coefficient of performance (COP) was relatively low when compared to conventional vapor compression refrigeration systems (VCRS), this limitation is not disadvantageous in this case because the system relies on renewable solar energy rather than electrical input.

The operational results confirm that the system effectively converts solar thermal energy into usable cooling, offering an alternative to costly, electricity-driven refrigeration systems. The low operational cost, environmental friendliness, and absence of moving mechanical parts minimize wear, noise, and vibrations, making the system highly suitable for both rural communities and urban users seeking to reduce electricity consumption. This project thus represents a promising step toward sustainable refrigeration solutions in regions where reliable electricity supply is lacking.

5.1.1 Key Findings

i. System functionality:

The solar-powered adsorption refrigeration system was able to operate efficiently using solar energy as its primary heat source. Despite its relatively low COP, it demonstrated practical cooling performance suitable for light-duty applications.

ii. Solar Energy Utilization:

The system proved effective in converting solar thermal energy directly into refrigeration without the need for an electrical compressor, thereby reducing energy costs and environmental impact.

iii. Design and material performance:

The design ensured durability and stable thermal operation, while the selected adsorbent–adsorbate pair (zeolite–water) provided a safe, non-toxic, and efficient working medium under varying thermal conditions.

iv. Societal impact:

The system offers a cost-effective and sustainable cooling alternative for rural areas with limited electricity supply and urban areas seeking lower energy tariffs, contributing to improved food and medical storage.

5.2 RECOMMENDATIONS

Based on the findings above, the following recommendations are proposed to improve system performance and promote further development of this solar adsorption refrigeration system:

5.2.1 System Design And Operation

i. The adsorption bed design can be modified to improve contact between the adsorbent and the heat source. Using fins or metallic matrices can enhance heat conduction within the bed, leading to faster regeneration and adsorption rates.
ii. Improved thermal insulation materials should be installed around the generator, condenser, and evaporator sections to reduce heat losses and maintain steady temperature gradients throughout the cycle

5.2.2 Performance Improvement

i. Conduct additional experiments to determine the best operational parameters for improving the coefficient of performance (COP).
ii. Explore the use of hybrid solar heating methods, combining direct solar concentration and auxiliary heat sources, to maintain steady operation even under low sunlight conditions.

5.2.3 Efficiency Optimization

i. Develop better control mechanisms for adsorption and desorption cycles to ensure balanced thermal operation.

ii. Investigate alternative adsorbent–adsorbate pairs or composite materials that may improve cooling efficiency and regeneration rates.

5.2.4 Future Research and Development

i. Optimization Of Adsorbent–Adsorbate Pair

Future work should focus on exploring alternative zeolite structures and other adsorbent– adsorbate combinations such as silica gel–water or activated carbon–methanol to compare adsorption capacity, cycle time, and achievable cooling temperature. Tailoring pore size and surface treatment could enhance adsorption kinetics and system performance.

ii. Improvement of solar collector efficiency:

Development of more advanced solar collector designs—such as evacuated-tube or concentrating collectors—would allow higher generator temperatures to be reached without auxiliary heating. Incorporating selective coatings and improved insulation could minimize thermal losses and increase overall energy utilization.

iii. Integration with smart control and monitoring systems:

The application of sensors, data loggers, and intelligent control algorithms (e.g., neural-network based controllers) can optimize cycle timing, valve operation, and switching between adsorption and desorption phases. This would ensure stable operation under fluctuating solar conditions and enhance the coefficient of performance (COP).

iv. Prototype Scaling And Long-Term Performance Evaluation:

Future research should involve scaling the system for practical applications, such as off-grid refrigeration or vaccine storage. Long-term testing under varying climatic conditions will provide valuable data on system durability, adsorbent degradation, and real-world energy savings.

In summary, this solar-powered adsorption refrigeration system has demonstrated that renewable energy can be effectively harnessed for sustainable cooling applications. With further design improvements and optimization, it holds great promise as a reliable and environmentally friendly alternative to conventional refrigeration systems.

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