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Review Article

Review and Development of Solar Thermal Adsorption Refrigeration Technology

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ABSTRACT
This paper delves into potential of solar thermal adsorption refrigeration systems (STAR) as a sustainable and environmentally friendly cooling solution. The core components and the two-phase operational cycle of these systems are detailed, highlighting the previous work on the STAR Technology has been discussed and critical roles of the vacuum chamber, freezer compartment and activated carbon adsorption bed. The cooling phase involve the evaporation of liquid ethanol, its adsorption on activated carbon, and subsequent heat extraction from the freezer compartment. This refrigeration on the other hand involves heating the adsorption bed to desorb ethanol which then condenses in vacuum chamber. This paper further explores the theoretical concept used in this system and the adsorption refrigeration cycle focusing on key stages of isosteric heating, isobaric desorption, isosteric cooling and isobaric adsorption. By leveraging solar energy as a renewable heat source this system offers an alternative to conventional refrigeration methods, reducing reliance on fossils fuels and mitigating greenhouse gases and the system is successfully developed

1. Introduction

In recent times, it has been observed that developing countries face a lack of consistent power supply across the nation, with electricity unavailable in certain rural areas. Due to this, hospitals encounter challenges in storing vaccines or antidotes that require low temperatures. To address this issue, research was conducted to identify a viable solution, and it was concluded that adsorption is one of the best approaches. The adsorption refrigeration cycle was studied and researched as the most suitable solution to this problem. After thorough analysis, it was concluded that a STAR system could be developed. This system is operated without requiring any power consumption, unlike the vapor Compression refrigeration System (VCRS) cycle. Temperatures as low as 2-6°C are capable of being achieved by it, making it suitable for storing medicines and vaccines. Various adsorbent pairs are used by the STAR system, with activated carbon powder and silica gel being selected for this study. A rigid network of colloidal silica connected to tiny grains of hydrated SiO_4 is featured by silica gel, an amorphous synthetic silica. Common silica gel types include A type, with pore diameters of 2-3 nm, and B type, with pore diameters of 0.7 nm. A specific surface area ranging from 100 to 1000 m^2/g is also offered by these materials [1].

The STAR system operates through specific phases. In the adsorption phase, the adsorbent material (e.g., activated carbon) is used to adsorb the refrigerant (e.g., ethanol) from the evaporator, which cools the surrounding space or substance. During the desorption phase, the saturated adsorbent is heated, often using solar thermal energy, causing the adsorbate to desorb and release heat. This phase typically occurs in a separate chamber or section of the system. Finally, during the regeneration phase, the adsorbent is cooled down and prepared for the next adsorption phase. This system operates as an open cycle.

Conventional refrigeration has been significantly enhanced human living standards but comes with notable environmental costs. About 9% of global electricity is consumed by it and nearly 1 billion tons of CO_2-equivalent emissions are contributed annually by it [2]. As climate change is accelerating, the need for cooling technologies is expected to surge. It is estimated by the World Bank that by 2050, energy use for cooling devices could rise by 300%, with countries in tropical and subtropical regions, such as India and Brazil, experiencing a 500% increase in cooling demand [3].

In addition to energy concerns, environmental hazards are created by traditional refrigerants. The ozone layer is damaged by chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) [4], while extremely high global warming potentials (GWPs) are exhibited by hydrofluorocarbons (HFCs), sometimes reaching levels 12,000 times that of carbon dioxide.

Alternative refrigeration solutions, particularly adsorptive systems, have been explored by recent research, with a focus on their technical and economic [5-6]. However, the environmental impact of these systems throughout their life cycles remains underexplored. A comprehensive approach to sustainability is offered by Life Cycle Analysis (LCA) by examining the environmental effects of products and processes across their entire life span [7]. Before this mathematical model and theoretical study was done, no successful development of a solar adsorption-based refrigeration system had been achieved. Successful and mainly theoretical studies have been performed.

2. Recent Development in the field of Adsorption Refrigeration System

Adsorption has long been studied for its applications in separation, purification, and thermally driven refrigeration systems. A porous solid material, characterized by its expansive surface area, considerable pore volume, and high capacity for adsorbing substances, has been at the core of this process. [8]

The surface of the solid has typically been in an unbalanced and unsaturated state. When exposed to a gas, an interaction has taken place due to the residual molecular forces on the solid surface, which have attracted and retained molecules, atoms, or ions from the gas. This interaction has arisen as the solid surface has sought to balance its molecular forces.

As a result, the concentration of the gas or liquid has become significantly higher near the solid surface compared to the surrounding bulk phase, regardless of the type of gas or vapor. This phenomenon, where the excess accumulation has occurred at the surface, has been termed adsorption [9].

The adsorption process is classified into two types: physisorption and chemisorption, based on the constraining forces involved during adsorption. In the physisorption process, the adsorbate molecules are attracted to the adsorbent surface by weak Van der Waals forces, which are similar to the molecular forces responsible for cohesion and vapor condensation into liquids. No changes in the chemical composition of the adsorption pair are observed [10].

In this process, the adsorbed molecules can be released by the application of heat, which typically does not exceed 80 kJ/mol. Physical adsorbents are capable of adsorbing multiple consecutive layers of the adsorbate gas, resulting in a multilayer thickness of the adsorbed phase.

In contrast, the chemisorption process is characterized by the involvement of valence forces arising from the sharing of electrons between the adsorbent and the adsorbate atoms. This interaction leads to a chemical reaction and the formation of a complex surface compound. The forces associated with these bonds are significantly stronger than the Van der Waals forces present in physisorption. Consequently, a much higher heat of adsorption, up to 800 kJ/mol, is required to release the adsorbate.[11] It should be noted that for most solid adsorbents commonly used in adsorption cooling systems, the adsorptive action is predominantly physical in nature.[12]

The concept of adsorption refrigeration is traced back to the 19th century, but its integration with solar thermal energy has been given prominence in recent decades. Early research was focused on the utilization of waste heat and low-grade thermal energy sources, which laid the foundation for solar-based systems. The rising need for eco-friendly cooling solutions was addressed through extensive research into adsorption materials and system designs.[13]

Adsorption can be categorized into two main types: physisorption and chemisorption, depending on the nature of the forces involved. In physisorption, the adsorbate molecules are drawn to the surface of the adsorbent through weak Van der Waals forces, similar to the forces responsible for molecular cohesion and the condensation of vapor into liquid. This type of adsorption does not alter the chemical composition of the interacting pair.[14]

Physisorption allows the adsorbed molecules to be removed by applying heat, typically requiring energy levels below 80 kJ/mol. Multiple layers of adsorbate gas can be held by physical adsorbents, resulting in a multilayered structure on the adsorbent's surface.[15]

On the other hand, chemisorption involves stronger interactions driven by valence forces, where electrons are shared between the adsorbent and adsorbate. A chemical reaction is induced by this process, forming a compound at the surface. The bonds in chemisorption are much stronger than those in physisorption, and significantly more energy is required to release the adsorbate, often reaching up to 800 kJ/mol.

3. Development of Test Facilities

The solar thermal adsorption refrigeration system is composed of three primary components: a vacuum chamber, a freezer compartment, and an adsorption bed filled with activated carbon. This system is operated in a two-phase cycle: cooling and regeneration. [16]

Cooling Phase: During this phase, liquid ethanol in the vacuum chamber is evaporated, producing ethanol vapor. The vapor is travelled to the adsorption bed, where it adheres to the activated carbon's surface. This adsorption process draws heat from the freezer compartment through the vacuum chamber walls, creating an evaporative cooling effect. The cooling phase continues until the activated carbon becomes saturated with ethanol.

Regeneration Phase: In this phase, the connection between the adsorption bed and the vacuum chamber is sealed, and the adsorption bed is heated. The applied heat causes the ethanol to desorb, increasing the vapor pressure within the adsorption bed. When the valve reconnecting the bed to the vacuum chamber is reopened, ethanol vapor flows back to the vacuum chamber, where it cools and condenses. This process resets the system for the next cooling cycle. This cycle can be continuously repeated to achieve and maintain low temperatures on the external wall of the vacuum tube.

Adsorptive Refrigeration Cycle: Isosteric Heating (1-2): Starting Point: The adsorbent is at the adsorption temperature, fully saturated with the adsorbate at evaporation pressure. Process: Solar heat increases the pressure and temperature while the adsorbate mass remains constant. Isobaric Desorption (2-3): Starting Point: The adsorbate reaches condensation pressure. Process: Continued heating drives the adsorbate as vapor to the condenser, where it releases heat and condenses into liquid. The adsorbent reaches its maximum regeneration temperature and minimum saturation level. Isosteric Cooling (3-4): Process: The adsorbent is cooled as additional heat is removed. The expansion valve is opened, allowing liquid adsorbate to flow into the evaporator. This reduces pressure and temperature, leading to vaporization of the adsorbate. Isobaric Adsorption (4-1):

Starting Point: The evaporator produces a coolingeffect. Process: The adsorbate vapor absorbs heat from its surroundings, vaporizes, and is re-adsorbed by the adsorbent. The adsorbent releases sensible and adsorption heat, returning to its adsorption temperature. The cycle then repeats as shown in fig 1.

The STAR (Solar Thermal Adsorptive Refrigeration) project aims to provide affordable, sustainable refrigeration solutions without relying on electricity. Emphasizing human-cantered design, the project focuses on creating systems that are accessible and practical for communities in need.

By utilizing a closed, cyclic system based on adsorption, the STAR technology operates independently of electrical power, making it ideal for regions with unreliable electricity access.[14]

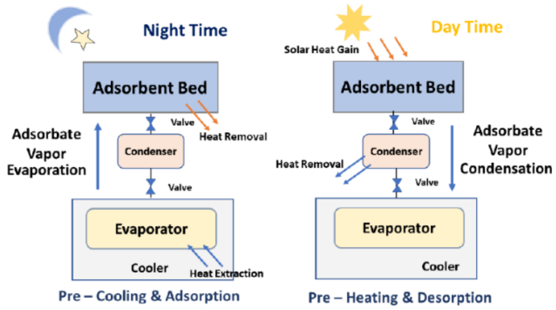

Figure 1. Schematic diagram of STAR Cycle

Design and fabrication of STAR System include Cooling Chamber, Evaporator, Solar collector, Daytime Heating and Desorption, Heat Exchanger Storage Basin and Valves.

Various Details of Components of STAR System.

- *Cooling Chamber*:

The cooling chamber is a crucial component of the vaccine refrigerator, designed to maintain a consistent low temperature as shown in fig 2. It achieves this through a combination of clever design features and careful engineering. Copper coil expansion system used inside the evaporator for cooled inside the chamber. It is Moisture barrier ,Low conductivity material The evaporator is surrounded by distilled water, which acts as a phase-change material. It absorbs heat and changes into ice, creating a stable cooling environment. The chamber is heavily insulated to minimize heat gain from the outside environment. The insulation material and thickness are carefully chosen to balance thermal efficiency and practicality The ethanol pipe, which is the only penetration through the insulation, is made of a low-conductivity material to reduce heat leakage as shown in fig 2 below.

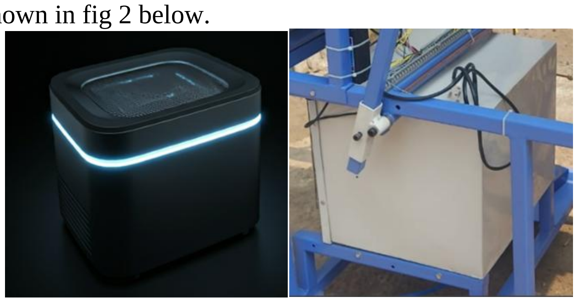

Figure 2. Cooling Chamber

- *Evaporator Design*

Stainless Steel: Used chamber due to its excellent corrosion resistance and hygienic properties. The thickness of the stainless steel should be sufficient to withstand the vacuum and pressure variations during operation.

Mild Steel: Used structural support and protect the insulation. The thickness of the mild steel should be sufficient to maintain the structural integrity of the chamber.

The evaporator design should consider the following factors:

Heat Transfer Surface Area: A larger surface area will enhance heat transfer efficiency. The design should incorporate features like fins or baffles to increase the surface area without significantly increasing the overall size of the evaporator.

Flow Distribution: The refrigerant should be evenly distributed across the evaporator surface to maximize heat transfer. This can be achieved through proper piping and distribution manifolds.

Pressure Drop: The pressure drops across the evaporator should be minimized to reduce the power consumption of the compressor.

Defrosting: A suitable defrosting method should be implemented to prevent ice buildup on the evaporator coils as shown in fig 3 below.

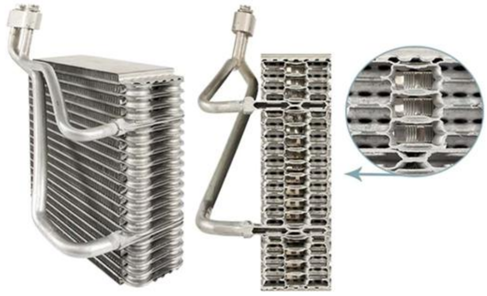

Figure 3. Evaporator

Solar Collector Specification and Design

Reflective and Insulating Layers:

Reflector Material: Aluminium reflector at the bottom surface to redirect and maximize heat absorption by the tubes as shown in fig 4 and 5 below.

Figure 4. Solar Collector

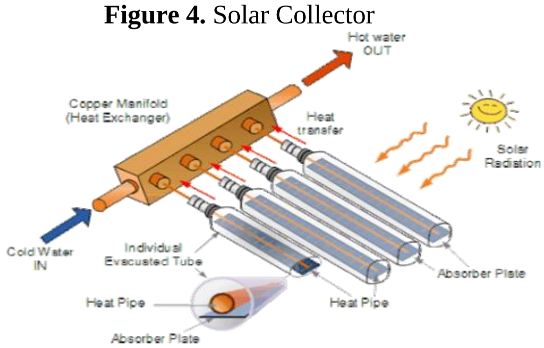

Figure 5. Bottom View

Design Considerations and Features

Activated Carbon Loading:

- The collector was designed to accommodate activated carbon, capable of adsorbing ethanol vapor
- Due to variations in carbon adsorption characteristics, the design includes provisions for additional capacity.
- Material Selection for Cost and Efficiency:
- Aluminum was chosen for the main construction due to its affordability and decent thermal conductivity.
- Welding aluminum was impractical in the given setting, so an adhesive-based sealing technique using silicon glue was adopted for an airtight construction.

Heat Distribution Mechanism:

- Inner Tube System: The inner tube is perforated with slits, allowing uniform ethanol vapor distribution throughout the carbon.
- Outer Framework: The tubes are held in place by steel headers, ensuring structural stability.
- Enhanced Heat Absorption, Greenhouse Enclosure
- A greenhouse-like structure surrounds the collector.
- Daytime Operation: The enclosure traps air to increase temperature within the collector.
- Nighttime Operation: Vents are opened to allow trapped air to escape, facilitating rapid cooling.

Condenser Design

The air-cooled condenser in the system is designed to effectively remove heat from the ethanol vapor, ensuring it condenses back into a liquid state for the subsequent cycle. It uses air circulation to facilitate the cooling process, with a well-structured design optimized for efficient heat dissipation.

- Fins: Fins are attached to the copper tubes to increase the surface area and enhance the heat dissipation process. These fins improve the heat exchange efficiency, particularly in conditions where the cooling system must work under varying environmental temperatures.
- Fan Design: The which plays a vital role in circulating air over the fins. This fan increases convective heat transfer by moving ambient air across the fins, thereby speeding up the cooling process of the ethanol vapor.
- Fabrication; The fan and condenser system whole system are fabricated at the Maharaja Agrasen Institute of Technology, Delhi, ensuring precise manufacturing and adherence to the required performance specifications for the system.
- Operational principal: Heat Transfer Process, Optimal performance of rapid cooling of ethanol vapor.
- Large surface area for heat exchange, which is essential for maintaining efficient cooling of the ethanol vapor.
- Copper tubes are critical for quick and efficient heat conduction.
- Fins for Enhanced Cooling: The addition of fins to the copper tubes further amplifies the heat dissipation capacity, ensuring that the system works optimally even in warmer conditions as shown in fig 6 below.

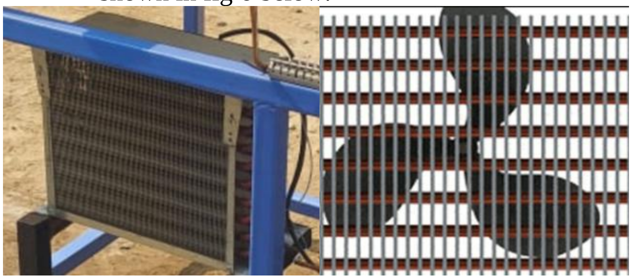

Figure 6. Condenser

The STAR system incorporates a comprehensive set of measuring devices and control panels to ensure precise monitoring and efficient operation. For pressure measurement, liquid-filled pressure gauges are installed on both the suction and discharge sides of the pump, ensuring accurate readings under operational conditions. A digital pressure transmitter and indicator provide real-time pressure data, enhancing system control. The flow rate is continuously monitored by a flow sensor with a digital indicator, while temperature variations are captured using a multi-channel digital temperature scanner. The electrical control system adheres to industry standards, featuring reliable on/off switches for user-friendly operation. The system ensures optimal thermal performance and system reliability as shown in fig 7 below.

Figure 7. Control Panel

The solar thermal adsorption system has been successfully fabricated. Details of our System are given below:

The solar flat plate collector system is a robust and efficient design thick glass top cover and aluminium reflector bottom surface ensure durability and maximize solar energy absorption. Thermal insulation is provided, the air-cooled condenser the evaporator chamber includes a stainless-steel chamber and mild-steel cover for optimal thermal retention as shown in fig 8 below.

Measurement and control are achieved through advanced instrumentation. The system incorporates a copper coil expansion mechanism within the evaporator, ensuring efficient operation.

Figure 8. Final Fabrication of Solar Thermal Adsorption Refrigeration System

4. Conclusions

In the present work paper advantages of STAR system is discussed. The paper highlights the detailed working of Solar Thermal Adsorption Refrigeration System with Different working pairs employed by different researcher.

Later a novel STAR Refrigeration System has been developed. Sustainable cooling technology where we use for Hospitals, sustainable Cooling, used in agriculture.

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