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Solar Adsorption Cooling

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Abstract-As the world grapples with climate change and energy sustainability, innovative cooling technologies are crucial for reducing carbon emissions. This study presents a groundbreaking study of solar adsorption cooling systems, a promising technology for building cooling applications. Using a transient model, analyze the impact of key design variables on the system's coefficient of performance (COP) and refrigeration capacity. Furthermore, we identify the optimal solar collector and storage tank volume and observe the properties of materials to minimize costs and maximize energy efficiency. This study provides a vital framework for the design and development of sustainable solar adsorption cooling systems, paving the way for widespread adoption in the built environment. It is a promising technology that harnesses solar energy to provide cooling, reduce reliance on fossil fuels, and mitigate climate change.

Keywords -Solar Energy , Adsorption Cooling , Activated carbon , Methanol .

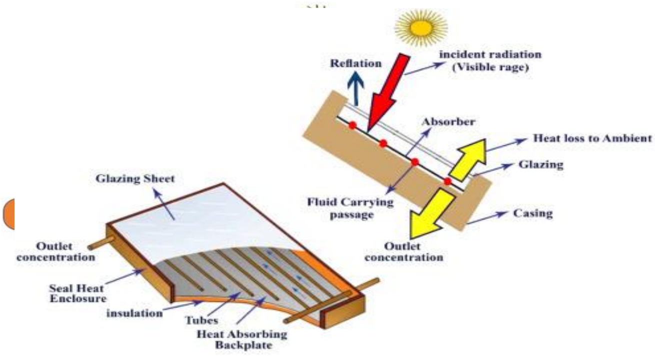
1. INTRODUCTION

Solar adsorption cooling systems have gained significant attention in recent decades as an environmentally friendly alternative to traditional vapor compression cooling systems (Goyal et al., 2015). These systems utilize low-grade heat sources, particularly solar energy, to drive the cooling process, making them an attractive option for reducing electricity consumption and mitigating global warming potential (Goyal et al., 2015; Sumathy et al., 2003).

The basic principle of solar adsorption cooling involves using solar energy to heat an adsorbent material, typically activated carbon or silica gel, zeolites which then adsorbs a refrigerant such as methanol or water (Islam & Morimoto, 2016; Luo et al., 2006). This process can generate cooling temperatures as low as -12°C, enabling ice production and air conditioning applications (Islam & Morimoto, 2016). Interestingly, some systems incorporate thermal energy storage to overcome the intermittent nature of solar radiation, allowing for continuous cooling production (Fadar, 2016).

2. SETUP

The solar adsorption refrigeration system figure (a), consists of several key components that work together to provide cooling using solar energy. At the heart of the system is the solar collector (adsorption bed), which contains an adsorbent material, such as activated carbon, silica gel, or zeolite, that has the ability to adsorb and desorb a refrigerant like ammonia or water. The collector is designed to absorb solar radiation, causing the adsorbent material to heat up and release the refrigerant in vapor form. This vapor then moves toward the condenser, which is a heat exchanger where the refrigerant gas releases heat to the surroundings and condenses into a liquid state. The condensed refrigerant is stored in a refrigerant storage tank, which acts as a buffer before the refrigerant enters the evaporator.



Fig(a) :- Schematic diagram of Solar Refrigeration

The evaporator is a crucial component where the liquid refrigerant undergoes phase change by absorbing heat from the refrigerator compartment, thereby lowering the temperature and providing the cooling effect. This cooling is achieved as the refrigerant evaporates, drawing heat from the surrounding space. The system also includes multiple control valves (V1, V2, and V3), which regulate the flow of the refrigerant at different points in the cycle. During the night or when solar radiation is not available, the solar collector cools down, allowing the adsorbent material to regain its adsorption capacity and reabsorb the refrigerant vapor from the evaporator, thus completing the cycle. The entire system is designed to operate without electricity, making it highly suitable for remote areas, off-grid refrigeration, and environmentally sustainable cooling applications. The simplicity of the design, combined with the use of renewable solar energy, makes this system an attractive alternative to conventional refrigeration methods, reducing both energy consumption and environmental impact.

3. APPARATUS

3.1. Solar Flate Plate Collector

A solar flate plate collector shown in figure (b) consists of several essential components that work together to capture solar energy and convert it into heat.

3.1.1 Absorber Plate

It is made of high thermal conductivity materials like copper, aluminum, or steel. It is coated with a selective black coating to maximize solar absorption while minimizing reflection losses. The plate is attached to fluid-carrying tubes to transfer heat efficiently.

3.1.2 Fluid Carrying Tubes

These tubes run beneath or through the absorber plate and carry the heat transfer fluid. They are usually made of copper or aluminum for efficient heat conduction. The tubes can be arranged in parallel patterns to optimize heat transfer.

3.1.3 Transperant Sheet

A sheet covers the top of the collector to reduce heat loss while allowing sunlight to enter. Tempered glass is commonly used as it is durable, transparent, and resistant to high temperatures. The glazing helps trap heat inside the collector by preventing convective and radiative heat losses.

3.1.4 Casing

The entire assembly is housed in a metallic or wooden frame to provide mechanical support and protect the components from environmental damage. It is designed to be weatherproof to withstand outdoor conditions. The back and sides of the collector are insulated to prevent heat loss to the surroundings.

Fig(b) :- Solar Flate Plate Collector

3.2. Condenser

The condenser in the solar adsorption refrigeration system is responsible for converting the refrigerant vapor into a liquid state by rejecting heat to the surroundings. It ensures the proper functioning of the cooling cycle by maintaining the flow of refrigerant between the adsorption bed and the evaporator.

3.2.1Heat Exchanger Tubes or Coils

Made of copper or aluminum to ensure high thermal conductivity. The refrigerant vapor flows through these tubes, transferring heat to the surrounding air or water.

3.2.2Cooling Fins

Metal fins may be attached to the tubes to increase the surface area for better heat dissipation. These fins improve the efficiency of heat rejection.

3.3. Evaporator

Evaporator in a solar adsorption refrigeration system, responsible for absorbing heat from the compartment and providing the cooling effect. It works by allowing the liquid refrigerant to evaporate, absorbing heat from the surrounding space.

3.3.1 Heat Exchanger Tubes or Coils

Made of copper or aluminum to ensure efficient heat transfer. These tubes carry the refrigerant and allow it to absorb heat from the compartment.

3.3.2 Expansion Valve or Capillary Tube

Controls the flow of liquid refrigerant entering the evaporator.Ensures that the refrigerant enters at low pressure and temperature, allowing efficient evaporation.

4. PROCEDURE

The system can be divided into two processes.

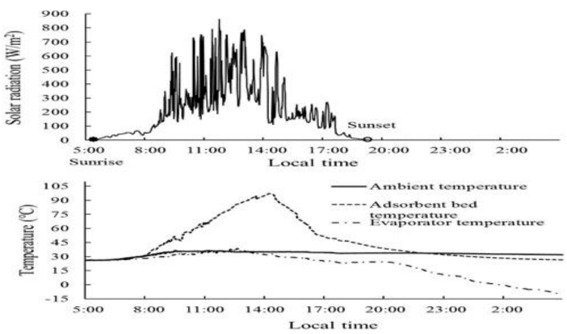
Fig(c) :- Temperature and Solar Radiation

4.1. Desorption (Heating Process - Daytime)

During the daytime, solar radiation heats the adsorption bed which contains an adsorbent material such as activated carbon, silica gel, or zeolite saturated with refrigerant. Solar radiation heats the adsorber, causing the adsorbent material to release the adsorbed refrigerant vapor. This process is called desorption removal of refrigerant from the adsorbent. The released refrigerant vapor flows toward the condenser. The condenser removes heat from the refrigerant vapor, converting it into liquid form. Heat is dissipated into the surroundings. The condensed liquid refrigerant is stored in a refrigerant storage tank for later use in the cooling cycle.

4.2. Adsorption (Cooling Process - Nighttime)

At night, when solar heating stops, the adsorption bed cools down and starts to adsorb the refrigerant vapor



again, creating a low-pressure environment that allows cooling to take place in the evaporator. As the adsorption bed cools, it starts to adsorb refrigerant vapor from the evaporator. This process creates a low-pressure zone inside the evaporator, allowing the refrigerant to evaporate. The liquid refrigerant from the storage tank enters the evaporator through an expansion valve (V3). Inside the evaporator, the refrigerant absorbs heat from the refrigerator compartment and evaporates, producing a cooling effect. The evaporated refrigerant moves back to the adsorber, where it is adsorbed again, completing the cycle.

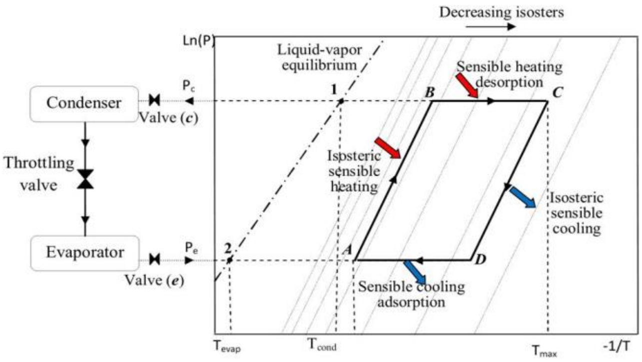
5. MATHEMATICAL EXPLANATION

Fig(d) :- Clapeyron diagram

5.1. Energy Balance for the Adsorption System

$$Q_{\text{solar}} = Q_{\text{des}} + Q_{\text{cond}} + Q_{\text{evap}} + W_{\text{net}}$$

Where: Q_{solar} = Heat input from the solar collector (J)
Q_{des} = Heat required for desorption of refrigerant (J)
Q_{cond} = Heat rejected at the condenser (J)
Q_{evap} = Heat absorbed by the evaporator for cooling (J)
W_{net} = Net work done by the system is negligible



$$Q_{\text{solar}} = Q_{\text{des}} + Q_{\text{cond}} + Q_{\text{evap}}$$

5.2. Solar Collector Energy Balance

$$Q_{\text{solar}} = I \cdot A \cdot \eta_{\text{collector}}$$

Where : I= Solar radiation intensity (W/m²)
A = Area of the solar collector (m²)
$\eta_{\text{collector}}$ = Efficiency of the solar collector
This heat energy is used to desorb the refrigerant from the adsorbent.

5.3. Desorption Process (Refrigerant Release)

$$Q_{\text{des}} = m_{\text{refrig}} \cdot h_{\text{des}}$$

Where: m_{refrig} = Mass of refrigerant released (kg)
h_{des} = Specific enthalpy of desorption (J/kg)
Desorption occurs at high pressure (P_h), and the refrigerant is released as vapor.

5.4. Condensation Process (Heat Rejection)

$$Q_{\text{cond}} = m_{\text{refrig}} \cdot h_{\text{cond}}$$

Where : h_{cond} = Specific enthalpy of condensation (J/kg)
This process occurs at constant high pressure.

5.5. Evaporation Process (Cooling Effect)

$$Q_{\text{evap}} = m_{\text{refrig}} \cdot h_{\text{evap}}$$

Where : h_{evap} = Specific enthalpy of evaporation (J/kg)
The cooling effect produced by the evaporator is determined by,

$$COP = Q_{\text{evap}} / Q_{\text{solar}}$$

Where: COP = Coefficient of Performance of the system
In solar adsorption systems, $COP$is typically between 0.2 - 0.6, depending on the adsorbent-refrigerant pair.

5.6. Adsorption Process (Refrigerant Absorption)
After evaporation, the adsorption bed cools, and the adsorbent reabsorbs the refrigerant vapor. The adsorption heat is released.

$$Q\text{ads} = m\text{refrig} \cdot h\text{ ads.}$$

This process occurs at low pressure (Pl).

5.7. Pressure-Temperature Relation
The adsorption system follows the Dubinin-Astakhov equation, which defines the relation between adsorbed mass and temperature:

$$W = W_0 \exp\left[-(RT/E)^n\right]$$

Where: W= Adsorbed refrigerant mass (kg/kg adsorbent)
W_0 = Maximum adsorption capacity
R= Universal gas constant (8.314 J/mol·K)
T= Temperature (K)
E= Adsorption potential (J/mol)
n= Adsorption coefficient
This equation helps in determining the adsorption/desorption characteristics of the system.

6. MATERIALS

Solar adsorption cooling systems utilize various materials with specific properties to enhance their performance and efficiency. The selection of solar collectors and adsorbent-adsorbate pairs is crucial for system optimization (Mahesh, 2017). Traditional flat plate, evacuated tube, and parabolic trough collectors are commonly used, providing temperature ranges of 60-80°C, 80-150°C, and 150-400°C, respectively (Mahesh, 2017). Evacuated tube collectors have demonstrated the highest efficiency in providing the necessary heat energy for adsorption cooling systems (Hakemzadeh et al., 2024). However, linear Fresnel reflectors and parabolic trough collectors show exceptional performance under clear sky conditions (Hakemzadeh et al., 2024). Several adsorbent-adsorbate pairs have been studied for their effectiveness in solar adsorption maintaining adsorption temperatures up to 117.2ºC and achieving evaporator temperature as low as -12°C on sunny days (Islam & Morimoto, 2016). Silica gel, water, and zeolite-water pairs are also widely used. The silica gel-water pair has demonstrated better performance compared to the SAPO-34 zeolite-water pair, with a coefficient of performance 1.93 times higher at optimal adsorption time (Liu et al., 2020). Composite adsorbents, such as zeolite 13X/CaCl2, have shown significant improvements in water uptake capacity. A 0.4g/g difference in equilibrium water uptake between 25 and 75°C at 870Pa was recorded for this composite adsorbent, which is 420% higher than that of pure zeolite 13X (Chan et al., 2012). These composite materials can potentially enhance the efficiency of solar adsorption cooling systems powered by low-grade thermal energy sources.

Properties	Activated carbon	Silica Gel	Zeolite
Composition	Carbon-based (typically from coal, coconut shell)	Amorphous silicondioxide	Crystalline aluminosilicate minerals
Surface Area	500-1500 m²/g	600-800 m²/g	400-800 m²/g
Pore Size	Microporous and mesoporous	Mesoporous	Microporous
Adsorbs	Gases, organic vapors, and odors	Moisture, water vapor	Water, gases like CO2, NH3, and hydrocarbons
Chemical Stability	Resistant to most chemicals, but oxidizes inair at high temperatures	Stable, but reacts with strong alkalis	Highly stable under most conditions
Moisture Absorption	Moderate	High	High

Properties	Methanol (CH3OH)	Ethanol (C2H5OH**)**	Ammonia (NH3)	Water (H2O)
Molecular Weight (g/mol)	32.04	46.07	17.03	18.02
Boiling Point (°C)	64.7	78.4	-33.3	100
Melting Point (°C)	-97.6	-114.1	-77.7	0
Density (g/cm³)	0.792	0.789	0.73	1.00

pH	Neutral to slightly acidic	Neutral	Basic (pH = 11)	Neutral (pH = 7)
Flammability	Highly flammable	Highly flammable	Flammable	Non-flammable
Toxicity	High	Moderate	Toxic in high doses	Non-toxic

7. CHALLENGES

Solar adsorption cooling systems face several challenges despite their potential as a clean and renewable energy-driven technology. Performance and efficiency issues are significant hurdles. Most adsorption systems deliver a coefficient of performance (COP) between 0.1 and 0.2, which is relatively low (Ojha et al., 2020). This low efficiency is partly due to the intermittent nature of solar energy and the inherent limitations of the adsorption process. Researchers are working on improving system designs and materials to enhance performance. For instance, integrating latent heat storage units has shown promise in improving solar COP and the daily cooling performance of solar adsorption cooling systems can be optimized by adjusting various parameters. These include solar hot water temp 0.096 to 0.13 for solar COP, and 2.6 to 3.4 for electric COP (Luo et al., 2006; Luo et al.2010).

CONCLUSION

Solar adsorption cooling systems have shown promising potential as an environmentally friendly and energy-efficient alternative to traditional cooling methods. These systems can effectively utilize low-grade heat sources, including solar energy and waste heat, to produce cooling effects. The performance of solar adsorption cooling systems varies depending on the working pairs used. Other working pairs, such as activated carbon fiber/methanol and activated carbon/methanol, have shown high adsorption capacities and solar COP values, making them suitable for various cooling applications. Especially in hot climates with abundant solar radiation. While improvements in materials and system design are necessary to enhance performance, this technology has the potential to contribute significantly to renewable energy-based cooling applications and climate change mitigation.

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