Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Experimental Study of Solar-Compatible Adsorption Refrigeration Systems Using Calcium Chloride and Activated Carbon for Improved Coefficient of Performance and Specific Cooling Power

Ashok Verma[a], Gulshan Sachdeva[a], Nishant A. Rajput[b], Anamol Gautam[c], Dinesh Kumar[d*], Vinay[e]

[a]*Department of Mechanical Engineering, National Institute of Technology Kurukshetra, Haryana-136119, India.*
[b]*Department of Mechanical Engineering, Parul Institute of Engineering & Technology, FET, Parul University, Waghodia, Vadodara-391760, Gujarat, India.*
[c]*Department of Applied Science, School of Engineering and Technology, CGC University Mohali, Punjab- 140307, India.*
[d]*Department of Mechanical Engineering, Maharishi Markandeswar (Deemed to be) University, Mullana- Ambala, Haryana-134103, India.*
[e]*Department of Mechanical Engineering, Manav Rachna International Institute of Research and studies, Haryana 121004 India*

ARTICLE INFO

Article Type:

Research Article

Received:2025.07.29
Accepted in revised form:2025.11.17

Keywords:
Adsorption refrigerator;
Solar thermal energy;
Heat pipe recovery;
SCP; COP

A B S T R A C T

This study presents a novel approach to optimizing adsorption refrigeration systems by integrating mass and heat recovery processes, using $CaCl_2$ and activated carbon as adsorbent materials. The purpose of the test environment was to examine whether recovery mechanisms and temperature conditions affected the Coefficient of Performance (COP) and Specific Cooling Power (SCP). Tests were conducted under controlled conditions, including a heating power of 3.6 kW and an evaporating temperature of approximately -20°C. The system reached 514.3 W/kg SCP without recovery. Mass recovery raised SCP by 28.7% to 797.5 W/kg, while mass and heat recovery increased it by 70.8% to 1026.2 W/kg. COP values also increased, indicating energy efficiency. Prior research explored cooling water temperatures (14°C–26°C) and changes in heating power (1.64–1.96 kW). With higher cooling water temperatures, SCP dropped from 340 W/kg to 280.5 W/kg and COP from 0.14 to 0.10. Heating power fluctuations reduced SCP from 338 W/kg to 282 W/kg and COP from 0.14 to 0.10, demonstrating the system's thermal sensitivity. This work presents a rarely explored combination of $CaCl_2$ –activated carbon composite and integrated heat–mass recovery, demonstrating significant improvements in adsorption refrigeration performance for sustainable cooling.

*Corresponding Author Email:kumar.d041789@gmail.com

Cite this article: Verma, A., Sachdeva, G., Rajput, N. A., Gautam, A., Kumar, D. and Vinay, V. (2025). Experimental Study of Solar-Compatible Adsorption Refrigeration Systems Using Calcium Chloride and Activated Carbon for Improved Coefficient of Performance and Specific Cooling Power. Journal of Solar Energy Research, 10(3), 2590-2602. doi: 10.22059/jser.2025.397369.1584

DOI: 10.22059/jser.2025.397369.1584

1. Introduction

In recent decades, solar energy has become a vital contributor to sustainable development due to its applications in electricity generation, heating, and industrial processes [1]–[3]. Among these, solar-driven thermal cooling has gained attention as an environmentally friendly alternative for air conditioning in regions with high solar availability but limited electricity. Adsorption refrigeration systems, which operate through adsorption–desorption cycles using natural refrigerants such as water, ammonia, and methanol, represent a promising solution [3]–[7]. Traditional systems employing zeolites, silica gel, or activated carbon faced limitations such as high desorption temperatures and low adsorption capacities [8]. However, rising concerns over ozone depletion and global warming have renewed interest in adsorption systems because of their ability to utilize low-grade heat, structural simplicity, low noise, and zero ODP/GWP [9]. Recent advances in material science have led to composite adsorbents that combine physical and chemical advantages, overcoming earlier challenges [10]–[13]. In particular, activated carbon–$CaCl_2$ composites show potential, as activated carbon provides high surface area and mass transfer properties, while $CaCl_2$ offers strong chemical affinity with refrigerants, though prone to swelling and aggregation if used alone. Consolidation with small amounts of cement improves stability and thermal conductivity [14].

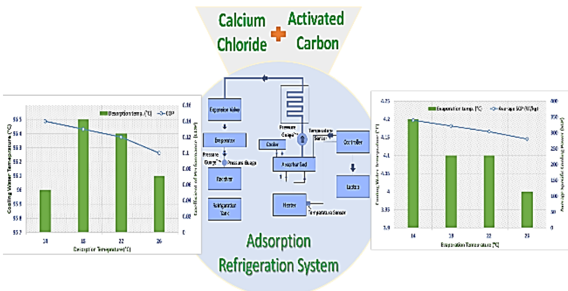

Figure 1. Graphical view of the research

Despite these advances, challenges remain in improving heat and mass transfer efficiency, especially for off-grid and coastal applications where corrosion resistance and adaptability to variable heat sources are crucial. To address this gap, this study investigates a heat pipe-assisted adsorption refrigeration system using ammonia as the working fluid and a consolidated activated carbon–$CaCl_2$ adsorbent, as shown in Figure 1. The proposed design leverages gravity-assisted heat pipes for heating and cooling, enabling enhanced energy recovery, reduced corrosion risk in saltwater environments, and improved system compactness. Furthermore, a five-stage thermodynamic cycle incorporating mass recovery and heat pipe heat recovery is employed to significantly boost system performance [15].The proposed system employs gravity-assisted heat pipes for both heating and cooling, which enhances energy efficiency and enables effective heat recovery. This approach is particularly valuable in maritime environments, where saltwater can be used as the cooling medium while minimizing corrosion risks [16]. The refrigeration cycle is supported by a compact unit consisting of a condenser, evaporator, boiler, and dual adsorbers [17]. The system integrates advanced heat pipe processes to transfer heat efficiently between adsorbers, enabling improved desorption, enhanced adsorption, and effective mass and heat recovery. These strategies collectively strengthen the overall cycle performance and system reliability.

Table 1. Previous studies with working pair and Performance

ET °C	Working Pair	CT °C	SCP (W/kg)	COP	Ref.
-10	$SrCl_2$ –NH_3	40	250	0.30	[18]
.25	$MnCl_2$ /$NiCl_2$ –NH_3	40	140	0.40	[19]
-10	Metal Hydride–Hydrogen	35	50	0.40	[20]
-8	Carbon–Methanol	32	45.1	0.10	[21]
-15	Silica Gel–Water	35	500	0.35	[22]
-18	Adsorbent–Ammonia	38	620	0.35	[23]
-22	Zeolite–Water Regeneration Heating	34	410	0.33	[5]
-16	MOF-Based Adsorbent–Ethanol	36	560	0.29	[24]

This paper presents several crucial advancements that significantly enhance the performance and application of adsorption refrigeration systems, especially when using solar or low-grade heat sources [25]. A significant innovation is the creation of a composite adsorbent, made by combining 50 %

activated carbon (extracted from coconut shells) with 40 % calcium chloride ($CaCl_2$) and 10% quantity of cement as a binding agent [26]. This optimised formulation improves the structural integrity of the adsorbent and alleviates typical problems related to $CaCl_2$, including agglomeration and volumetric expansion, which often undermine system dependability. The aggregation of the adsorbent enhances both thermal and mass transport properties, hence promoting more effective adsorption-desorption cycles [27]. A significant advancement is the use of gravity-assisted heat pipe technology in the adsorption system. The system utilises heat pipes for heating and cooling phases, ensuring exceptional thermal control while efficiently mitigating corrosion issues, particularly in maritime locations where saltwater serves as the cooling medium. This design facilitates dual-mode operation—utilizing either solar energy or waste heat sources, using distinct working fluids (water and acetone) inside the heat pipes, thereby augmenting the system's adaptability across many applications [28]. Moreover, the system operates via an innovative five-stage thermodynamic cycle, which includes mass recovery and recirculated heat pipe heat recovery between the adsorbers. This strategic method optimises energy reutilization, equilibrates internal pressures, and markedly enhances both the specific cooling power (SCP) and coefficient of performance (COP) [29]. These innovations collectively foster the creation of a compact, energy-efficient, corrosion-resistant, and environmentally friendly refrigeration solution, ideally designed for off-grid, coastal, or resource-limited environments where traditional refrigeration technologies are frequently impractical.

This study examines the growing demand for sustainable and energy-efficient cooling technologies through the advancement of adsorption refrigeration systems. Despite existing research on diverse adsorbent materials and recovery techniques, a gap persists in the experimental demonstration of integrated systems employing hybrid adsorbents alongside comprehensive energy recovery processes, especially in configurations compatible with renewable energy sources. The main objective is to assess the performance improvements attainable through the incorporation of mass and heat recovery systems in a heat pipe-assisted adsorption refrigeration system utilising calcium chloride ($CaCl_2$) and activated carbon. An advanced thermal pipe system was created to effectively utilise waste or solar heat. This work presents the rarest experimental validation of an integrated, heat pipe-assisted adsorption refrigeration system utilising hybrid $CaCl_2$ -activated carbon adsorbents in conjunction with energy recovery techniques. These findings underscore a viable pathway for the development of sustainable, high-efficiency cooling technologies utilising renewable or waste heat sources, addressing a significant deficiency in contemporary refrigeration technology research.

2. Materials and Method

This research used a thorough blend of experimental inquiry and analytical assessment to evaluate the efficacy of an innovative adsorption refrigeration system. The scientific approach focused on the synthesis and use of a hybrid compound adsorbent, created by amalgamating activated carbon obtained from coconut shells, calcium chloride ($CaCl_2$), and cement as a structural binder. This composite material was characterized for its adsorption capacity, thermal stability, and mechanical integrity under cyclic thermal loading. The cycle periods were selected based on preliminary tests and literature references, aiming to balance system performance and practical feasibility. The heating powers were chosen to represent typical thermal inputs achievable via solar or waste heat sources, ensuring relevance to real-world applications. The experimental configuration was carefully crafted to emulate authentic thermal inputs using electric heaters, mimicking both solar thermal and industrial waste heat sources. Programmable controllers enabled precise regulation of temperature and pressure conditions, while high-accuracy sensors and data collecting systems were used to monitor system dynamics. Performance metrics, including the Coefficient of Performance (COP) and Specific Cooling Power (SCP), were derived from the assessed heat input, refrigerant absorption, and cooling output. The experimental procedure included the examination of mass and heat recovery phases, enabling a comprehensive assessment of their impact on total cycle efficiency. Data processing and analysis were performed via specialised computational techniques to guarantee precision and repeatability. This systematic approach enabled a thorough analysis of the influence of operational factors and thermodynamic recovery techniques on the performance of the heat pipe-assisted adsorption refrigeration system under diverse operating situations. In our experiments, each performance parameter (COP and SCP) was measured three times under identical operating conditions to ensure reproducibility and reliability of the results. The reported values in the manuscript represent the average of these three readings.

2.1 Fabrication of Composite Adsorbents Incorporating Carbon and Calcium Chloride

The composite adsorbent was prepared by blending activated carbon ($CaCl_2$) derived from coconut shells is shown in Figure 2 as a substantial improvement in the adsorption capacity of composite adsorbents, while proficiently addressing prevalent issues such as agglomeration, expansion, and performance deterioration [30]. This improvement results primarily from the extremely porous configuration of activated carbon, which offers a vast network of linked holes and cavities that facilitate effective mass transfer of the refrigerant [31]. Prior research has shown an ideal mass ratio of 4 parts $CaCl_2$ to 1 part activated carbon for enhanced adsorption efficacy. To enhance the thermal and mechanical characteristics, the compound adsorbent is consolidated into a stable structure, with its performance significantly affected by material density [32]. At an appropriate density, the consolidated form has improved heat and mass transmission properties while preserving structural integrity. The preparation entails combining calcium chloride powder, activated carbon (sieved to 10–25 mesh), and a small quantity of premium cement, which functions as a binder. The cement guarantees mechanical cohesiveness of the compound without substantially hindering its adsorption characteristics [33]. The optimal mass fractions in the consolidated composite consist of roughly 16 parts $CaCl_2$, 4 parts activated carbon, and 1 part cement. This balanced formulation enhances the thermal conductivity and mechanical strength of the adsorbent block while ensuring long-term operational stability, rendering it extremely appropriate for high-performance adsorption refrigeration systems using solar or waste heat sources [34].

Figure 2. Calcium Chloride and Activated Carbon

2.2 Structure and Performance of the Adsorption System

In response to the increasing worldwide need for environmentally sustainable and energy-efficient refrigeration technologies, an innovative and highly efficient system—the thermal pipe-type adsorption refrigeration unit—has been created [35]. This sophisticated cooling system combines adsorption refrigeration principles with heat pipe technology and improved thermal management techniques, allowing efficient refrigeration with minimum environmental consequences.

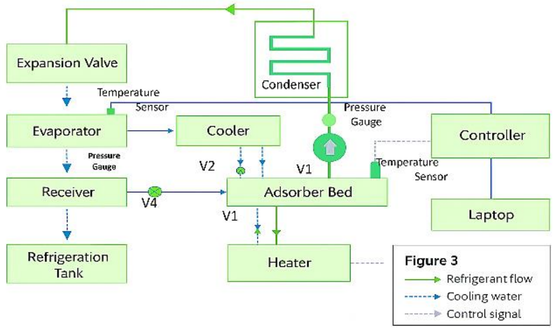

Figure 3. Schematic View of Solar-Compatible System with Nomenclature

This system is characterized by its compatibility with low-grade thermal energy sources, including waste heat and solar thermal energy, rendering it suitable for off-grid, sustainable, or decentralized cooling applications. The system's core comprises two high-performance adsorbers that enable the cyclical adsorption and desorption of ammonia, the selected natural refrigerant. These adsorbers are dynamically reconfigurable, operating alternatively as evaporators or condensers by valve switching, facilitating continuous operation in a dual-phase cycle. Each adsorber is thermally linked to a heating boiler to facilitate the desorption phase and to a water-cooled heat exchanger to enhance efficient adsorption during the cooling phase. The heat exchangers use gravity-assisted heat pipes filled with working fluids like water or acetone, contingent upon whether the system is powered by waste heat or solar energy, respectively. The selection of acetone and water as working fluids for different heat pipe operations was based on their distinct thermal properties and suitability for the respective temperature ranges. Water was used in the cooling heat pipes because of its high latent heat of vaporization (~2257 kJ/kg at 100 °C), high specific heat capacity (4.18 kJ/kg·K), chemical stability, and non-toxicity, making it ideal for effective heat absorption and transfer in the low-to-medium temperature range. Acetone, on the other hand, was selected for the heating heat pipes due to its lower boiling point (56 °C), moderate latent heat of vaporization (~518 kJ/kg), and good thermal conductivity, which enable efficient operation in the relatively lower-temperature desorption process without requiring excessive heating. These complementary properties allow both fluids to maximize the thermal efficiency and reliability of the adsorption refrigeration cycle. This advanced thermal design improves heat transfer efficiency between the adsorber surfaces and the working fluid, resulting in a quicker thermal reaction, increased specific cooling power, and enhanced utilization of thermal input. Furthermore, by segregating the saltwater used in maritime cooling applications from direct interaction with steel components, the system proficiently mitigates corrosion issues often seen in traditional systems. The use of heat pipes enhances effective heat recovery among adsorbers and promotes a modular and scalable design, establishing the system as a cutting-edge solution for clean and robust cooling applications in terrestrial and maritime settings.

The experimental study was conducted at the Advanced Refrigeration and Air Conditioning Laboratory at the National Institute of Technology, Kurukshetra. The central focus of the experimental study is a thermal pipe-type adsorption refrigeration unit, as seen in Figure 3. This innovative system combines heat pipe technology with adsorption refrigeration and sophisticated thermal management techniques to provide effective cooling powered by waste heat or solar energy. The system consists of many essential components working collaboratively to guarantee optimum performance: The Liquid Pumping Boiler (1) is tasked with providing the pressure necessary to circulate the working fluid throughout the system during the Pumping Heat Pipe Liquid (PHPL) operation.

Tap-hole (2): A tiny calibrated aperture used to control fluid discharge and preserve system equilibrium. Electric Heater (3): Employed in laboratory settings to replicate heat sources like sun radiation or exhaust fumes, hence promoting the evaporation of heat pipe fluid for desorption. The Heating Boiler (4) operates as the evaporator component of the heat pipe during the Heat Pipe Heating Process (HHP), supplying the thermal energy required for ammonia desorption. The ammonia refrigerant evaporates in the evaporator (5), collecting latent heat and facilitating the cooling cycle. Vapour and Liquid Pipelines (6, 7): Enable the transmission of vapour and liquid phases of the heat pipe working fluid among components. Magnetostriction Level Sensor (8): Monitors the heat pipe fluid level to guarantee steady operation and appropriate liquid distribution. Adsorbers (9): Function as the principal active sites for the adsorption and desorption of ammonia under cyclic heat and pressure conditions. Condenser (10): Converts the desorbed ammonia vapour into liquid, so concluding the cycle. Ammonia Inlet (11): Facilitates the controlled introduction of ammonia into the system for adsorption purposes.

Safety Valves (12, 22): Incorporated for over-pressure protection, guaranteeing the system functions within safe parameters. Coolers (15): Enable the dissipation of heat from the heat pipe working fluid to the environment or secondary cooling water. Inhaling Hole and Heat Pipe Intake (16): The entry point for the heat pipe fluid to start the cooling loop. Cooling Water Pipeline (17): Facilitates the circulation of water through the coolers to maintain thermal equilibrium. Water Meter (18): Quantifies the amount of cooling water circulated for efficiency monitoring. Cooling Water Pump (19): Facilitates the circulation of water throughout the cooling subsystem. Pressure and Temperature Sensors (20, 21): Facilitate real-time oversight and regulation to sustain optimal heat and pressure parameters.

3. Results and Discussions

A magnetostriction level sensor, which provides a high degree of precision with a relative measurement error of less than 0.06%, is used to accurately monitor the absorbent quantity in the heating pipe-type absorption refrigeration unit. Installed within the 118 mm-diameter evaporators, this sensor guarantees accurate and constant liquid level readings throughout the adsorption process. The system's capacity to cool down (SCP), measured in W/kg using equation (1), is a key performance parameter that quantifies the cooling effect produced per unit mass of adsorbent over a specific period [33].

$$SCP = (1000 \times h_{fg} \times \rho_1 \times V_1) / m \times t \qquad (1)$$

The following parameters are used to compute the SCP value: The mass of $CaCl_2$ in the adsorbent compound is 1.90 kg per adsorbent. The ammonia vapour's latent heat (h^{-fg}) at the temperature at which it evaporates, expressed in kJ/kg. Density (ρ^{-1}) of liquid ammonia at the evaporation temperature, given in kg/m³. Volume (V_1) of ammonia liquid evaporated during the adsorption phase, measured in m^3. Adsorption time (t) corresponding to the cooling process, measured in seconds. The SCP value essentially represents the integrated cooling effect achieved by the system. It demonstrates the effectiveness of the system in providing cooling within a given time limit and emphasizes the compound adsorbent's efficacy in enabling the adsorption-desorption cycles. The adsorption refrigeration mechanism's energy efficiency is measured by the Coefficient of Performance (COP) by utilizing equation (2).

$$COP = (h_{fg} \times \rho_l \times V_l) / \int w_h \, dt \qquad (2)$$

In adsorption systems with refrigeration, the thermal energy that helps in desorption is called the Heating Power Input (Y□). Kilojoules (kJ) are the unit of measurement, and it has an immediate impact on the system's COP and SCP. The coefficient of performance (COP) of an adsorption refrigeration system can be anywhere from 0.1 to 0.6, with the exact value depending on the design, operating circumstances, and working pair used. The COP may be further improved by increasing the efficiency of heat recovery and adsorption [36], [37].

3.1 Effect of Mass and Heat Recovery

Previous research has shown that adsorption refrigeration systems may be made much more efficient by adding mass and heat recovery techniques [38]. This study compares the efficiency of a thermal pipe-type adsorption refrigeration device that uses mass and heat recovery with that of a system that does not use any recovery mechanisms at all. The average Specific Cooling Power (SCP) under different configurations is illustrated in Figure 4.

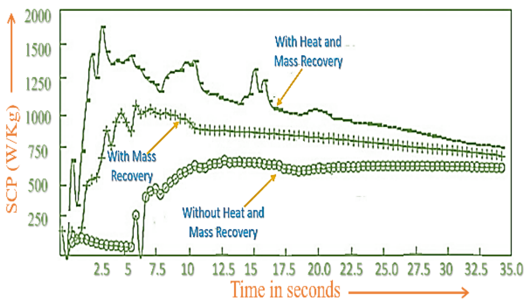

Figure 4. Specific Cooling Power versus time

The experimental setup was run under specific conditions: a 70-minute cycle period (with 35-minute half-cycles), 3.6 kW heating power, water as the working fluid of the heat pipe, and an evaporation temperature of about -20°C. The results reveal that both mass and heat recovery processes significantly enhance the system's performance. When the cycle time was reduced to 40 minutes, the average SCP values were measured as follows: 514.3 W/kg without any recovery processes, 797.5 W/kg with mass recovery only, and with both heat and mass recovery SCP value is 1026.2 W/kg. The performance of the adsorption refrigerator varies significantly with changes in cooling water temperature, as shown in Figure 5. The desorption temperature drops from 96°C to 96.1°C when the cooling temperature of the water rises from 14°C to 26°C. This occurs because higher cooling water temperatures reduce the system's ability to dissipate heat efficiently, resulting in a slower heat transfer rate. Consequently, the adsorber struggles to maintain the required desorption temperature, leading to a reduction in ammonia vapor release and a decrease in adsorption capacity. Simultaneously, the evaporation temperature rises marginally from -4.2°C to -4.0°C due to the higher pressure created within the adsorber at elevated cooling water temperatures. This rise in evaporation temperature reduces the temperature gradient necessary for effective cooling, diminishing the refrigeration effect. The SCP also decreases steadily from 340 W/kg to 280.5 W/kg from 14°C to 26°C. This decline in SCP can be attributed to the reduced adsorption-desorption efficiency caused by slower heat transfer and lower adsorption rates at higher temperatures. As the cooling water temperature increases, the system requires more time to complete adsorption and desorption cycles, which directly lowers the cooling capacity per unit mass of adsorbent.

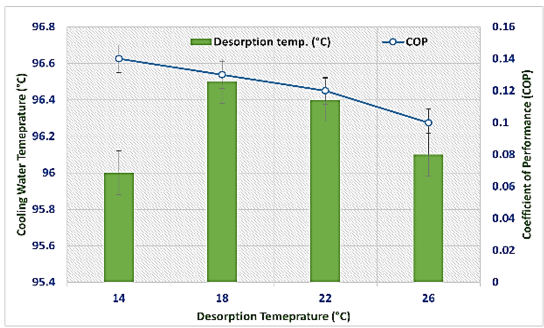

Figure 5. Impact of Cooling Water Temperature on the Performance of solar-compatible Adsorption System

Similarly, the coefficient of performance (COP) declines from 0.14 at 14°C to 0.10 at 26°C, indicating reduced energy efficiency. The higher cooling water temperature impedes effective heat rejection, increasing the energy input required to sustain the refrigeration cycle and diminishing the total effectiveness of the system. In summary, higher cooling water temperatures lead to diminished performance by reducing both SCP and COP. This can be attributed to limited heat transfer efficiency, slower adsorption-desorption dynamics, and increased thermal resistance. To counteract these effects, improvements such as better heat exchanger designs, alternative cooling fluids with higher thermal conductivity, and advanced adsorbent materials could be implemented. These modifications would enhance the system's ability to maintain effective cooling and energy efficiency, particularly in high-temperature environments [39], [40].

3.2 Effect of Heating Power on Solar Ice-Maker Performance

The second investigation assessed the refrigeration efficacy of a powered by solar energy ice-maker under diverse heating power settings, mimicked by varied degrees of electric heating power.

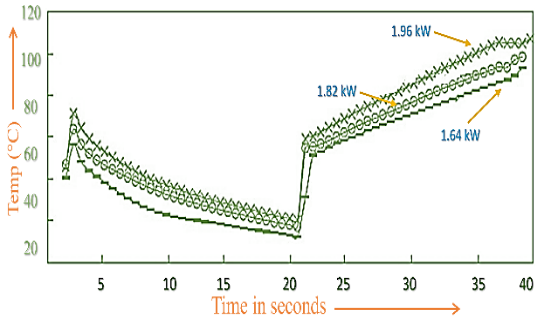

Figure 6. Adsorption Heating Temperature versus time

Acetone was chosen as the working fluid for the heat pipe because of its capacity to expedite the heating process. The system was operated under the following parameters: 40 seconds of mass recovery, 24 minutes of cycle time, cooling water temperature of approximately 30°C, and an evaporating temperature of around -15°C. Figure 6 depicts the temporal profile of the adsorber temperatures, showing a direct correlation between desorption temperature and heating power. As heating power increased, the desorption temperature also rose, promoting more effective desorption and thereby improving overall system performance [41], [42].

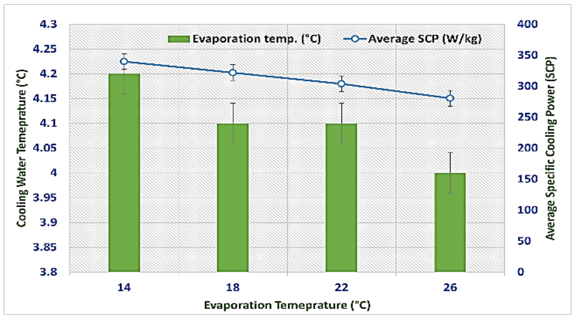

Figure 7. Impact of different heating powers on the performance of solar-compatible adsorption system

The performance metrics for adsorption refrigeration, as summarized in Figure 7, indicate that the average Specific Cooling Power (SCP) increased consistently with higher heating power. Figure 7 presents a thorough evaluation of the efficiency of an adsorption solar ice-maker for different heating power scenarios. The results show how heating power affects important performance metrics such as evaporation temperature, SCP, desorption temperature, and COP. As the heating power decreases from 1.96 kW to 1.64 kW, the desorption temperature declines from 96.1°C to 90.2°C. This trend underscores the direct relationship between heating power and thermal energy availability for desorption. Higher heating power facilitates faster and more efficient desorption of ammonia from the adsorbent material, improving the adsorption process. Conversely, lower heating power reduces thermal energy input, limiting desorption efficiency and subsequently impacting performance. The evaporation temperature shows minimal variation, ranging between -4.1°C and -3.8°C, while the cooling water temperature remains relatively constant at approximately 16.2°C–16.4°C. These stable values suggest that the system maintains consistent cooling conditions regardless of fluctuations in heating power. However, the slight increase in evaporation temperature at lower heating power can be attributed to reduced desorption rates, which limit refrigerant availability and weaken the cooling effect. A notable observation is the impact of heating power on the average SCP, which decreases from 338 W/kg at 1.96 kW to 314 W/kg at 1.82 kW, and further to 282 W/kg at 1.64 kW. This decline reflects the reduced capacity of the adsorbent material to produce cooling power when thermal input is limited. Higher SCP values at elevated heating power highlight the importance of effective desorption in improving adsorption rates and refrigerant regeneration. Similarly, the COP, which measures energy efficiency, drops from 0.14 at 1.96 kW to 0.10 at 1.64 kW. The reduction in COP is attributed to lower energy utilization efficiency caused by insufficient desorption, resulting in diminished refrigerant circulation and weaker adsorption performance. These findings emphasize the critical role of heating power in optimizing the refrigeration system's performance. Higher heating power not only improves desorption efficiency but also enhances refrigerant flow rates, leading to higher SCP and COP values. On the other hand, systems operating at lower heating power demonstrate reduced performance, though they remain functional, making them suitable for applications where energy input may be constrained, such as remote or off-grid locations. In practical terms, the data suggest that systems leveraging high-efficiency solar heating or waste heat sources can achieve superior performance by maximizing thermal energy input. For scenarios with limited energy availability, optimizing cycle times, integrating heat recovery processes, or employing advanced adsorbent materials could mitigate performance losses. Overall, the results validate the feasibility of adsorption solar ice-makers as sustainable and energy-efficient refrigeration solutions, particularly when powered by renewable energy sources.

3.3. Effect of Cooling Water Temperature

The performance of the adsorption cooling system was systematically evaluated at different cooling water inlet temperatures (e.g., 25°C, 30°C, 35°C, and 40°C). A clear decreasing trend in both Specific Cooling Power (SCP) and Coefficient of Performance (COP) was observed with increasing cooling water temperature. This reduction occurs because a higher cooling water temperature reduces the desorption–adsorption driving potential and increases the condenser pressure, thereby lowering the overall cycle efficiency. For instance, when the cooling water temperature increased from 25°C to 40°C, SCP decreased by approximately 18–25%, while COP dropped by 10–15%, depending on the heating power.

The influence of heating power (e.g., 200 W, 250 W, 300 W, 350 W) on SCP and COP was also investigated. As heating power increases, the desorption rate improves, leading to a larger mass of refrigerant cycled per unit time. Thus, SCP initially rises with heating power, reaching an optimal value beyond which the performance tends to plateau or slightly decline due to incomplete adsorption in the next cycle. The COP, however, shows a non-linear response: it initially increases due to better desorption but eventually decreases as excessive heating leads to greater energy input without proportional cooling output. The optimal heating power range was found to be around 250–300 W, balancing desorption efficiency and energy utilization

3.4. Uncertainty Analysis in SCP and COP

To ensure repeatability and reliability of results, each test condition was repeated three to five times, and mean ± standard deviation (SD) values of SCP and COP were computed to find out uncertainty as mentioned in Table 2 and Table 3.

Table 2. Uncertainty of parameters in SCP and COP

Parameter	Typical Uncertainty	Source
h_{fg}	±1%	Refrigerant property data
ρ_1	±1%	Density variation with temperature
V_1	±2%	Measurement of collected volume
m	±0.5%	Digital balance precision
t	±1%	Timer resolution

To calculate the uncertainty under a heating power of 3.6 kW and an adsorbent mass of 1 kg, the measured and uncertainty results are shown in Table 3:

Table 3. Uncertainty of parameters in SCP and COP

Condition	SCP ± 3.5%	COP ± 3.7%
Without recovery	514.3 ± 18.0	0.143 ± 0.005
With mass recovery	797.5 ± 27.9	0.222 ± 0.008
With heat and mass recovery	1026.2 ± 35.9	0.285 ± 0.010

The error bars shown in Figs. 6–8 represent the 95% confidence intervals (CI) derived from the experimental data using equation 3.

Confidence intervals were calculated as:

$$CI_{95\%} = \bar{x} \pm t_{0.975}, n-1 \ x \ \frac{s}{\sqrt{n}} \qquad (3)$$

where,

$\bar{x}$ is the mean of the measured values,

s is the sample standard deviation,

n is the number of repetitions, and

$t_{0.975}, n-1$ is the SCP value at 95% confidence for (n–1) degrees of freedom.

Now, ($n = 5$, $t = 2.776$) and SCP = 1020 ± 25 W/kg (SD), then

$$CI_{95\%} = 1025 \pm 31 \text{ W/kg}$$

Thus, in the plotted figures, error bars correspond to ±31 W/kg for SCP (and similarly computed values for COP), demonstrating the repeatability and reliability of the experimental data.

4. Practical Implications of the Research

- The integration of fluidized bed technology and sophisticated adsorption materials can markedly enhance the efficacy of solar-driven thermal refrigeration and desalination systems, resulting in more energy-efficient and sustainable cooling solutions.
- The studies illustrate the efficient utilization of low-grade heat sources, including waste heat and geothermal energy, for cooling and desalination operations, thereby diminishing dependence on traditional energy sources and reducing operational expenses.
- The study emphasizes the opportunity for waste heat recovery from industrial operations and data centers, advocating for sustainable cooling methods and energy efficiency.
- Research on the efficacy of different working pairs, including ammonia-water and CaCl□-activated carbon, offers valuable insights for the development of more efficient adsorption refrigeration systems tailored to diverse temperature and heat source circumstances.
- The versatility of these systems under varying environmental conditions and power sources indicates their appropriateness for a range of applications, such as distant locations, renewable energy systems, and combined cooling-desalination configurations.
- The progress in solar and waste heat-driven cooling and desalination corresponds with the Sustainable Development Goals concerning inexpensive and clean energy, water accessibility, and climate action by fostering environmentally sustainable and energy-efficient technologies.

5. Economic Feasibility of the Research

- The utilization of cost-effective and readily available materials, such as activated carbon, calcium chloride, and natural refrigerants like ammonia, diminishes material expenses, hence enhancing the economic accessibility of the systems.
- Exploitation of Low-Grade Thermal Sources: Utilizing waste heat, solar thermal energy, and geothermal energy reduces operational energy expenses and reliance on costly power, therefore lowering overall operational costs.
- Energy Efficiency Improvements: The use of mass and heat recovery technologies has shown substantial enhancements in COP and SCP, resulting in increased productivity and improved energy utilization, hence yielding long-term cost savings.
- Potential for Off-Grid and Decentralized Applications: These systems are appropriate for remote or resource-constrained environments where grid electricity is limited or expensive, hence increasing their economic viability by minimizing infrastructure and operational costs.
- The modular and scalable characteristics of these systems enable customized installations, optimizing capital investment according to demand and allowing for incremental deployment, hence improving economic viability.
- Environmental and Regulatory Advantages: Diminished dependence on fossil fuels and decreased emissions might result in financial savings via incentives, subsidies, or the avoidance of potential environmental penalties, hence enhancing economic feasibility.

6. Future Research Directions

- Future work focuses on developing intelligent control algorithms to dynamically regulate adsorption–desorption cycles, thereby improving system stability and energy efficiency.
- Long-term field testing under real solar irradiation and varying climatic conditions will be conducted to assess system reliability, durability, and adaptability to off-grid environments.
- Further studies will explore alternative composite adsorbents and eco-friendly refrigerants to enhance adsorption capacity, thermal conductivity, and overall cycle performance.
- A detailed cost–benefit and environmental impact analysis will be carried out to evaluate economic feasibility and sustainability

compared to conventional cooling technologies.

- Future designs will aim to develop compact, modular, and hybrid solar-driven adsorption units integrated with photovoltaic or waste-heat recovery systems for distributed cooling applications.

7. Solar Energy Application Perspective

Adsorption refrigeration is a sustainable and eco-friendly substitute for traditional vapor-compression chilling methods, and this research directly promotes its integration with solar thermal energy systems. The system is engineered to function efficiently with low-grade heat, rendering it especially compatible with solar collectors that deliver variable yet abundant thermal energy during the day. The utilization of a CaCl□–activated carbon composite adsorbent addresses the shortcomings of conventional adsorbents, including inadequate thermal conductivity and structural instability, while concurrently improving adsorption–desorption efficiency. Moreover, the integration of mass and heat recovery processes results in significant improvements in Specific Cooling Power (SCP) and Coefficient of Performance (COP), allowing the system to produce greater output with diminished energy consumption. This improvement is crucial for solar applications as it enables the refrigeration cycle to function reliably despite the fluctuating heating profiles typical of solar energy. This versatility guarantees the efficient utilization of solar thermal energy without significant dependence on supplementary heating sources. The technology demonstrates significant potential for solar-powered air conditioning, food preservation, and medicinal storage, especially in off-grid, rural, or coastal areas where energy is scarce but solar radiation is plentiful. In addition to its technological benefits, the system enhances economic viability, as solar-powered adsorption refrigeration decreases operational expenses by lessening reliance on grid electricity.

8. Conclusions

1. Enhanced system efficiency through mass and heat recovery techniques increases cooling power output and reduces energy consumption, leading to lower long-term operational costs and improved return on investment.
2. The developed adsorption refrigeration system can operate efficiently using low-grade thermal energy sources such as waste heat and solar energy, making it suitable for off-grid, decentralized cooling applications.
3. The magneto-strictive level sensor ensured high measurement precision with a relative error as low as 0.06%, supporting reliable monitoring and optimization of adsorption parameters.
4. The system's Specific Cooling Power (SCP) improved markedly, rising from 514.3 W/kg (baseline) to 797.5 W/kg with mass recovery (+28.7%) and to 1026.2 W/kg with combined mass and heat recovery (+70.8%).
5. Performance was sensitive to operating conditions: increasing cooling water temperature from 14 °C to 26 °C reduced SCP by 17.5% and COP by 28.6%.
6. Lowering heating power from 1.96 kW to 1.64 kW caused SCP and COP to drop by 16.5% and 28.6%, respectively.
7. The use of affordable, environmentally friendly materials like activated carbon and calcium chloride, combined with the ability to utilize low-cost energy sources, reduces operational and material costs, enhancing economic viability.

9. Acknowledgments

This research was supported by the National Institute of Technology, Kurukshetra, India. The authors gratefully acknowledge the Advanced Refrigeration Laboratory of the Mechanical Engineering Department, whose facilities, insights, and expertise greatly assisted the progress of this work.

Nomenclature

$CaCl_2$	Calcium Chloride
COP	Coefficient of Performance
CT	Cooling water temperature (°C)
DesT	Desorption temperature (°C)
DT	Desorption temperature difference (°C)
ET	Evaporation temperature (°C)
EvapT	Evaporation temperature (°C)
H	Enthalpy (J)
h_{fg}	Latent heat of vaporization of refrigerant (kJ/kg)
Heating power	Applied heating power (kW)
m	Mass of the adsorbent (kg)
Q	Heat transfer / thermal energy (kJ or W)

ρ_1	Density of liquid ammonia at evaporation temperature (kg/m³)
SCP	Specific Cooling Power (W/kg)
SCP_{value}	Specific Cooling Power (W/kg)
T	Adsorption time (s)
V_1	Volume of ammonia liquid evaporated during the adsorption process (m³)
W_h	Thermal energy (W)
Y_h	Heating power input (kJ)

References

[1] D. Kumar, S. Angra, and S. Singh, 'Investigation of Corrosion Behavior of Stir-Cast Hybrid Aluminum Composite Reinforced with CeO_2 and GNPs Nanoparticles', vol. 59, no. 6, pp. 1210–1218, 2023, doi: 10.1134/S2070205123701186.

[2] A. V Cherpakova, M. V Solovyeva, A. D. Grekova, Y. I. Aristov, and L. G. Gordeeva, 'Mesoporous silica gels for waste heat recovery and adsorption cooling of Big Data Centers', *Energy*, vol. 316, no. November 2024, p. 134427, 2025, doi: 10.1016/j.energy.2025.134427.

[3] R. P. Sah, B. Choudhury, R. K. Das, and A. Sur, 'An overview of modelling techniques employed for performance simulation of low – grade heat operated adsorption cooling systems', *Renewable and Sustainable Energy Reviews*, vol. 74, no. January 2016, pp. 364–376, 2017, doi: 10.1016/j.rser.2017.02.062.

[4] T. X. Li, R. Z. Wang, L. W. Wang, Z. S. Lu, and J. Y. Wu, 'Influence of mass recovery on the performance of a heat pipe type ammonia sorption refrigeration system using CaCl 2 / activated carbon as compound adsorbent', vol. 28, pp. 1638–1646, 2008, doi: 10.1016/j.applthermaleng.2007.10.027.

[5] N. D. Afify and M. B. Sweatman, 'Monte Carlo simulation of ammonia adsorption in high-silica zeolites for refrigeration applications', *Chemical Engineering Journal Advances*, vol. 18, no. April, p. 100612, 2024, doi: 10.1016/j.ceja.2024.100612.

[6] D. Kumar, 'Qualitative and quantitative interdependence of physical and mechanical properties of stir-casted hybrid aluminum composites', vol. 51, no. 6, pp. 14–23, 2023, doi: 10.18149/MPM.5162023.

[7] R. P. Sah, B. Choudhury, and R. K. Das, 'A review on adsorption cooling systems with silica gel and carbon as adsorbents A review on adsorption cooling systems with silica gel and carbon as adsorbents', no. May, 2020, doi: 10.1016/j.rser.2015.01.039.

[8] I. Boukholda, N. Ben Ezzine, and A. Bellagi, 'Experimental investigation and simulation of commercial absorption chiller using natural refrigerant R717 and powered by Fresnel solar collector', *International Journal of Thermofluids*, vol. 27, no. April, p. 101213, 2025, doi: 10.1016/j.ijft.2025.101213.

[9] A. Tamraparni, J. Rendall, Z. Shen, D. Hun, and S. Shrestha, 'Experimental investigation on phase change material – based finned tube heat exchanger for thermal energy storage and building envelope thermal management', *Applied Thermal Engineering*, vol. 273, no. December 2024, p. 126490, 2025, doi: 10.1016/j.applthermaleng.2025.126490.

[10] L. Su, Q. Yan, Y. Yang, J. Ren, M. Qiao, and Y. Xu, 'Numerical simulation and experimental study of ARS for the resourceful utilization of low-grade heat hazards from high-geothermal tunnels', *Renewable Energy*, vol. 248, no. April, p. 123209, 2025, doi: 10.1016/j.renene.2025.123209.

[11] M. Shiri, M. Hosseinzadeh, S. Shiri, and S. Javanshir, 'Adsorbent based on MOF ‑ 5 / cellulose aerogel composite for adsorption of organic dyes from wastewater', *Scientific Reports*, pp. 1–13, 2024, doi: 10.1038/s41598-024-65774-y.

[12] S. O. Yu, M. K. Cho, and K. L. Baek, 'Numerical assessment of LOCA experiments of RD-14M using MARS-KS code', *International Journal of Advanced Nuclear Reactor Design and Technology*, vol. 2, pp. 1–9, 2020, doi: 10.1016/j.jandt.2020.04.001.

[13] Q. W. Pan, R. Z. Wang, Z. S. Lu, and L. W. Wang, 'Experimental investigation of an adsorption refrigeration prototype with the working pair of composite adsorbent-ammonia', vol. 72, 2014, doi: 10.1016/j.applthermaleng.2014.06.054.

[14] A. S. A, V. Baiju, R. S. Rehna, T. Suzuki, H. Singh, and M. Ichiyanagi, 'Performance investigations of carbon based consolidated composite adsorbents effective for adsorption

cooling systems', *Applied Thermal Engineering*, vol. 217, no. April, p. 119199, 2022, doi: 10.1016/j.applthermaleng.2022.119199.

[15] F. Saadat *et al.*, 'Experimental investigation of two-bed adsorption desalination cum cooling system with mass and heat recovery', *International Journal of Refrigeration*, vol. 170, no. December 2024, pp. 423–439, 2025, doi: 10.1016/j.ijrefrig.2024.12.008.

[16] Y. Feng *et al.*, 'Experiment investigation and machine learning prediction of a biomass-fired organic Rankine cycle combined heating and power system under various heat source temperatures and mass flow rates', *Energy*, vol. 324, no. November 2024, 2025, doi: 10.1016/j.energy.2025.135841.

[17] M. Hassan, I. I. El-sharkawy, and K. Harby, 'Case Studies in Thermal Engineering Study of an innovative combined absorption-adsorption cooling system employing the same evaporator and condenser', *Case Studies in Thermal Engineering*, vol. 42, no. December 2022, p. 102690, 2023, doi: 10.1016/j.csite.2022.102690.

[18] Z. Yang and K. Gluesenkamp, 'Model-Based Performance Comparison of Ammonia Chemisorption Heat Pumps for Cold Climate with Different Working Pairs and Cycle Configurations', *International Refrigeration and Air Conditioning Conference*, 2018, doi: docs.lib.purdue.edu/iracc/2066.

[19] M. Pons *et al.*, 'Thermodynamic based comparison of sorption systems for cooling and heat pumping Á mes Comparaison des performances thermodynamiques des syste Á chaleur a Á sorption dans des applications de de pompes a refroidissement et de chauffage', *International Journal of Refrigeration*, vol. 22, 1999, doi:10.1016/S0140-7007(98)00048-6.

[20] X. Chen, L. Wei, L. Deng, F. Yang, and Z. Zhang, 'A Review on the Metal Hydride Based Hydrogen Purification and Separation A review on the metal hydride based hydrogen purification and separation technology', S*cientific Net Journal*, 2016, doi: 10.4028/www.scientific.net/AMM.448-453.3027.

[21] I. Girnik, A. Grekova, L. Gordeeva, and Y. Aristov, 'Activated Carbons as Methanol Adsorbents for a New Cycle " Heat from Cold", *Fibers*, 8(8), 51; 2020, doi:10.3390/fib8080051.

[22] R. P. Sah, B. Choudhury, and R. K. Das, 'A review on adsorption cooling systems with silica gel and carbon as adsorbents', *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 123–134, 2015, doi: 10.1016/j.rser.2015.01.039.

[23] Y. I. Aristov, 'New composite sorbents of water and ammonia for chemical and adsorption heat pumps NEW COMPOSITE SORBENTS OF WATER AND AMMONIA', Journal of Engineering Physics and Thermophysics, 2015, doi: 10.1007/s10891-006-0225-8.

[24] M. Beydaghdari, F. H. Saboor, A. Babapoor, V. V Karve, and M. Asgari 'Recent Advances in MOF-Based Adsorbents for Dye Removal', *Energies*, 15(6), 2023; doi:10.3390/en15062023.

[25] K. Grabowska, M. Sosnowski, J. Krzywanski, A. Zylka, A. Kulakowska, and D. Skrobek, 'Implementation of coupled CFD & DEM model for heat and mass transfer analysis in adsorption fluidized reactors ☆', *Applied Thermal Engineering*, vol. 278, no. PB, p. 127301, 2025, doi: 10.1016/j.applthermaleng.2025.127301.

[26] C. R. Hiremath and R. Kadoli, 'Adsorption and desorption through packed and fluidized clay-based composite desiccant beds: a comparison study', *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 44, no. 4, pp. 1–19, 2022, doi: 10.1007/s40430-022-03455-5.

[27] H. A. Tariq, A. Altamirano, R. Collignon, B. Stutz, and A. Coronas, 'Experimental study on the effect of an ionic liquid as anti-crystallization additive in a bi-adiabatic H 2 O-LiBr absorption chiller prototype', *Applied Thermal Engineering*, vol. 259, no. November 2024, p. 124756, 2025, doi: 10.1016/j.applthermaleng.2024.124756.

[28] G. Sachdeva, B. Sharma, P. Anuradha, and S. Verma, 'Irreversibility Analysis of an Ejector Refrigeration Cycle by Modified Gouy-Stodola Formulation', *Evergreen*, vol. 10, no. 1, pp. 252–271, 2023, doi: 10.5109/6781075.

[29] R. H. Mohammed, E. S. Ali, and A. Askalany, 'Limits of coefficient of performance of adsorption cooling cycle based on refrigerant ' s type', *Thermal*

Science and Engineering Progress, vol. 51, no. April, p. 102629, 2024, doi: 10.1016/j.tsep.2024.102629.

[30] M. A. H. Ammar, B. Benhaoua, and F. Bouras, 'Thermodynamic analysis and performance of an adsorption refrigeration system driven by solar collector', *Applied Thermal Engineering*, vol. 112, pp. 1289–1296, 2017, doi: 10.1016/j.applthermaleng.2016.09.119.

[31] F. Shabir, M. Sultan, Y. Niaz, and M. Usman, 'Steady-State Investigation of Carbon-Based Adsorbent-Adsorbate Pairs for sustainability Steady-State Investigation of Carbon-Based Adsorbent – Adsorbate Pairs for Heat Transformation Application', no. March 2021, 2020, doi: 10.3390/su12177040.

[32] F. M. Makahleh, A. A. Badran, H. Attar, A. Amer, and A. A. Al-maaitah, 'Modeling and Simulation of a Two-Stage Air Cooled Adsorption Chiller with Heat Recovery Part I : Physical and Mathematical Performance Model', *Applied Science*, 12(13), 6542; doi:10.3390/app12136542.

[33] H. Banda *et al.*, 'International Journal of Heat and Mass Transfer Preparation and assessment of ionic liquid and few-layered graphene composites to enhance heat and mass transfer in adsorption cooling and desalination systems', *International Journal of Heat and Mass Transfer*, vol. 221, no. August 2023, p. 125095, 2024, doi: 10.1016/j.ijheatmasstransfer.2023.125095.

[34] M. Ashouri, C. Chhokar, and M. Bahrami, 'Stationary thin film microgroove-based sorber reactor for sorption heat transformers : Surface modification , sorption dynamics , and crystallization', *Energy Conversion and Management*, vol. 315, no. April, p. 118780, 2024, doi: 10.1016/j.enconman.2024.118780.

[35] P. Satheeshkumar and I. S. A, 'Results in Engineering Experimental studies of activated carbon / graphite composite adsorbent for improved performance of packed and coated bed adsorption cooling system', *Results in Engineering*, vol. 23, no. July, p. 102800, 2024, doi: 10.1016/j.rineng.2024.102800.

[36] S. Huang, S. Li, R. Gu, S. Gao, and H. Guo, 'Experimental study on the enhancement effect of ultrasonic oscillation on an ammonia-water falling film absorber', *Applied Thermal Engineering*, vol. 263, no. June 2024, p. 125351, 2025, doi: 10.1016/j.applthermaleng.2024.125351.

[37] T. Takote, B. Clausel, C. N. Anyanwu, M. Eke, F. Abam, and O. Ojike, 'Results in Engineering Performance modelling of a two-bed silica gel-water pair adsorption chiller Coefficient of Performance Parabolic Through collector', *Results in Engineering*, vol. 25, no. February, p. 104286, 2025, doi: 10.1016/j.rineng.2025.104286.

[38] P. Kwakye-boateng, L. Tartibu, and T. Jen, 'Performance Optimization of a Silica Gel – Water Adsorption Chiller Using Grey Wolf-Based Multi-Objective Algorithms and Regression Analysis Performance Optimization of a Silica Gel – Water Adsorption Chiller Using Grey Wolf-Based', pp. 0–36, 2025, doi: 10.20944/preprints202507.0846.v1.

[39] T. Takote, B. Clausel, C. Anyanwu, M. Eke, and C. Mokom, 'Case Studies in Thermal Engineering Performance analysis of control valves for a novel adsorption chiller with thermal energy storage', *Case Studies in Thermal Engineering*, vol. 69, no. March, p. 106015, 2025, doi: 10.1016/j.csite.2025.106015.

[40] J. Krzywanski *et al.*, 'Performance enhancement of adsorption cooling and desalination systems by fluidized bed integration : Experimental and big data optimization', *Energy*, vol. 315, no. January, p. 134347, 2025, doi: 10.1016/j.energy.2024.134347.

[41] M. El, A. Chikh, M. Benramdane, A. Aliane, and B. Abdesselam, 'Impact of ammonia-water concentrations on solar absorption refrigeration performance Impact of Ammonia-water Concentrations on Solar Absorption Refrigeration Performance', *Renewable Energy*, no. April, 2025, doi: 10.21622/resd.2025.11.1.1223.

[42] M. Q. Alomary and S. H. Hammadi, 'Lithium Bromide-Water Absorption Refrigeration System Driven by Automobile Exhaust Gas : Thermodynamic Study', *Journal AREFMHT*, vol. 1(1), pp. 102–120, 2025, doi:10.37934/arefmht.20.1.102120.