

Evaluation of New Composite Adsorbents for Solar-Driven Adsorption Refrigerator

Ahmed N. Shmroukh¹□, Essam Hares², Osama Hamdy³, Mostafa Abouelsoud¹



Abstract Sustainability, nature conservation, and energy economy remain the significant points of the global community focus. Due to the rapid growth in the world wide consumption of limited conventional energy and the environmental consideration for refrigerant agents' choice, solar-driven adsorption refrigerators (SAR) have been the focal of extensive research for cooling and refrigeration applications subjected to meet the fast increase in refrigeration needs of the developing countries such as Egypt. A new two composite adsorbents consist of 95wt% silica gel powder with 5wt% activated carbon powder (SGC1) and 90wt% silica gel powder with 10wt% activated carbon powder (SGC2), used with water as a refrigerant agent in a solar adsorption refrigerator installed in Upper Egypt. These adsorbents were evaluated as eco-friendly and low-cost cooling storage for cooling fruits and vegetables within a convenient storage environment. The experiments were done under the weather conditions of Qena City in Upper Egypt. The main results showed that the best obtained coefficient of performance (COP) was about 0.174 for SGC1. The specific cooling power (SCP) value was about 0.0199 kW/kg for SGC1. Moreover, the delivered evaporator temperature by the adsorption refrigerator can reach about 2.8-1.6°C. These results revealed that the proposed new adsorbents are beneficial for storing vegetables and fruits in remote and rural areas where electrical power sources are insufficient or unavailable.

Keywords: Solar adsorption refrigerator; Silica gel; Eco-friendly; Storage

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List of symbols

A_b	adsorption bed total area (m ²)	t_c	cycle time (s)
$C_{p,w}$	water specific heat kJ/kg.K	z	measured value (-)
I	incident solar radiation (W/m ²)	Greek symbol	
\dot{m}	water mass flow rate (kg/s)	δr	results uncertainty
m_a	composite adsorbent quantity (kg)	Abbreviations	
N	number of measured values (-)	COP	coefficient of performance
Q_c	power of cooling (kJ)	SAR	solar adsorption refrigeration systems
Q_s	input solar based heat (kJ)	SCP	specific cooling power
T_h	hot temperature (°C)	SGC	silica gel powder with activated carbon powder
T_R	refrigeration temperature (°C)		

1 Introduction

In recent decades, environmentally friendly refrigeration systems received considerable attention due to global warming and Ozone layer depletion [1,2]. On the other hand, traditional refrigeration systems consume enormous amount of fossil fuels to be driven. Therefore, solar adsorption refrigeration systems (SAR) with efficient adsorbents and clean refrigerants as water can be treated as an intrinsic solution for such environmental problems [3]. Some features of SAR include but are not restricted to: simple design, being eco-friendly, no moving parts, suitable for portable applications, employing natural refrigerants, and low energy intensity and that way meeting the existing global regulations [4]. However, these systems are still under the aim of performance improvement [5].

Several researches were accomplished on using silica gel/water as adsorption pair in SAR. Chua et al. [6] investigated experimentally water adsorption characteristics onto two types of silica gels. Their results revealed that at 31 °C the maximum

adsorption capacity of type RD silica gel reached about $0.45 \text{ kg/kg}_{\text{ads}}$, and for type A silica gel reached about $0.39 \text{ kg/kg}_{\text{ads}}$. Pan et al. [7] studied experimentally a developed silica gel/water based adsorption refrigerator considering heat and mass recovery. Their proposed system results showed that the cooling power, coefficient of performance (COP), and specific cooling power (SCP) were reached about 42.8 kW , 0.51 , and $125 \text{ W kg/kg}_{\text{ads}}$, respectively. Moreover, Ng et al. [8] analyzed experimentally the adsorption isotherms of three different types of silica gel. Their results demonstrated that at a regeneration temperature of $90 \text{ }^\circ\text{C}$ about 95% of the three silica gel types can be regenerated completely, and type RD gave the highest adsorption uptake at $30 \text{ }^\circ\text{C}$ of $0.36 \text{ kg/kg}_{\text{ads}}$. While, El-Sharkawy et al. [9] performed a theoretical study on solar adsorption refrigerators using silica gel/water adsorption pair, working under the weather conditions of Jeddah in Saudi Arabia, Aswan, and Cairo in Egypt. Their results demonstrated that the maximum cooling capacity of their proposed system reached about 15.8 kW for Aswan and 14.8 kW for both Cairo and Jeddah climate conditions. Furthermore, Zhu et al. [10] compared advanced four different types of adsorption beds with silica gel/water working pairs. The results demonstrated that the COP and SCP of the proposed beds can reach up to 0.30 and $198.4 \text{ W kg/kg}_{\text{ads}}$. Moreover, He et al. [11] proposed experimentally a compact adsorption refrigerator used for automobiles, with a volume of about 40 L . They found that at $95 \text{ }^\circ\text{C}$ regeneration temperature the highest cooling capacity was 1.5 kW . Vodianitskaia et al. [12] examined silica gel particle size effect on COP, SCP and net cooling power of adsorption refrigerator worked with silica gel/water adsorption pair. Their proposed system achieved high values of COP, SCP, and cooling power which reached up to 0.53 , 68 W/kg , and 143 W at regeneration temperature of $80 \text{ }^\circ\text{C}$. Furthermore, Liu et al. [13] studied experimentally a pure silica gel adsorbent with water refrigerant in a solar adsorption refrigerator. Their experimental test rig is built in Beijing City in China. Their proposed system results showed that COP and SCP were reached about 0.256 , and $8.13 \text{ W kg/kg}_{\text{ads}}$, respectively.

From the mentioned point of view, it can be observed that using composite adsorption pairs in adsorption refrigerators still need essential development and research work to develop more efficient and compact adsorption refrigerators. The novelty of the present work is to use composite adsorbents consisting of silica gel powder and activated carbon powder with different weight percentages,

for increasing water uptake, enhancing both heat and mass transfer in the solar adsorption bed, and improving both COP and SCP of the proposed solar refrigerator.

2 Materials and Method

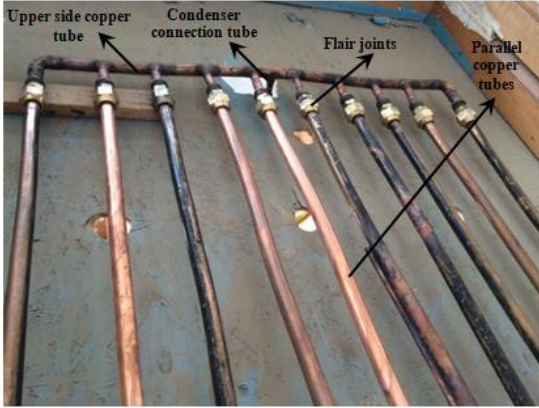
The proposed SAR is illustrated in the following Figure.1, the prototype is constructed and tested in Qena Faculty of Engineering garden ($26^\circ 10' \text{ N}$ and $32^\circ 43' \text{ E}$) [14,15], this prototype helped in evaluating the operating parameters and feasibility of using such type of solar adsorption refrigerator in harsh climates for food reservation. The proposed solar adsorption refrigerator has the following components: a thermally insulated adsorption bed with 0.48 m^2 effective area (0.8 m length \times 0.6 m width) equipped with 10 parallel red copper tubes spaced by 0.04 m , an air-cooled condenser, an evaporator with 10 L effective volume, and refrigerant piping. During daytime the composite adsorbent contained in the solar-driven adsorption bed is heated by solar radiation, this promoted the refrigerant molecules (water) to be desorbed from the composite adsorbent (silica gel powder with activated carbon powder) and transformed into vapor. Then, the water vapor is condensed in the free convection air cooled condenser and directed towards the evaporator till the end of this desorption process. While, during nighttime the adsorbent is cooled gradually involving the refrigerant adsorption process to be started, producing the required cooling action in the evaporator.



Fig.1 Proposed solar adsorption refrigerator.

The copper tubes of the adsorption bed have an internal diameter of 0.019 m , they are backed with the proposed 3 kg of composite adsorbents before each experiment. Regarding the first experiment, the well

mixed composite adsorbent consisted of 95wt% silica gel powder and 5wt% activated carbon powder, which can be named SGC1. While for the second experiment, the well mixed composite adsorbent consisted of 90wt% silica gel powder with 10wt% activated carbon powder, which can be named SGC2. Type-T thermocouples are attached in the required measuring points to accurately measure the adsorption bed, evaporator, condenser, and ambient temperatures, Figure 2 illustrates the piping and the final prototype of the adsorption bed container.



(a)



(b)

Fig.2 Adsorption bed assembly: a) copper tube connections, b) adsorption bed after packaging.

3 Proposed system performances

To evaluate the proposed SAR performance, essential parameters are required. One of the most essential parameters is the coefficient of performance (COP) of the solar adsorption refrigerator, which is the ratio of the average heat of cooling (Q_e) produced by the system in kJ to the input solar based heat (Q_s) to the system in kJ and it is calculated according to Eq. (1) [16].

$$COP = \frac{Q_e}{Q_s} \quad (1)$$

Subsequently, to determine the average cooling power of the proposed solar adsorption refrigerator, Eq. (2) can be used [17].

$$Q_e = \dot{m} C_{p,w} (T_h - T_R) t_c \quad (2)$$

Where \dot{m} , $C_{p,w}$, T_h , T_R , t_c , are water mass flow rate in kg/s, water specific heat kJ/kg.K, the hot temperature in °C, the refrigeration temperature in °C, and the cycle time in s, respectively. Moreover, the solar heat received by the adsorption bed can be is calculated by Eq. (3) [18].

$$Q_s = \int I(t) A_b dt \quad (3)$$

Where I is the incident solar radiation in W/m^2 , it is measured by using a sensitive digital pyranometer, and A_b is the adsorption bed total area m^2 . On the other hand, the specific cooling power (SCP) in W/kg_{ads} is one of the essential parameters for evaluating the performance of the proposed solar adsorption refrigerator, it can be determined by the relation (4) [19].

$$SCP = \frac{\dot{m} C_{p,w} (T_h - T_R)}{m_a} \quad (4)$$

Where m_a is the composite adsorbent quantity in kg, it is measured using a sensitive electronic scale. Regarding uncertainty and error analysis, the following procedure is used for calculating the uncertainty propagation [20, 21], and Table 1 clarifies the obtained values from the calculations.

$$\delta r = \sqrt{\left(\frac{\partial r}{\partial z_1} \delta z_1\right)^2 + \left(\frac{\partial r}{\partial z_2} \delta z_2\right)^2 + \dots + \left(\frac{\partial r}{\partial z_N} \delta z_N\right)^2} \quad (5)$$

Where δr is the uncertainty results, z is the measured value and N is the number of measured values [22]. Table 1 shows both measured and determined parameters uncertainty calculations' data.

Table 1. Error data for the determined and measured variables.

Parameter	Error (% of reading)
Solar radiation intensity	Up to ± 1 [14]
Temperature	± 0.1 [18]
COP	± 1.1 [1]
SCP	± 0.9

4 Discussion of the experimental results

Under the climatic condition of Qena City in the Upper Egypt zone, the proposed SAR is tested, during the period from 6:00 a.m to 6:00 p.m of almost two identical clear days on the 19th and 21st of September 2021.

The daily average variation of solar radiation intensity and adsorption bed, evaporator, condenser and ambient temperatures of SAR when using composite adsorbents SGC1 of 95wt% silica gel powder and 5wt% activated carbon powder, with water as a refrigerant on 19 Sep. 2021, is illustrated in Figure 3. The maximum solar radiation intensity of 1111 W/m² is available at noontime. Thereafter the amount of available solar radiation intensity decreases till the end of the test. The adsorption bed temperature reached its maximum value of 125 °C at 1:00 p.m then it was reduced gradually, due to water desorption from the heated adsorption bed. While the evaporator temperature reached its lowest value of 2.1 °C at 3:00 a.m due to water adsorption in the cooled adsorption bed. Regarding the ambient and condenser temperatures, both profile trends are nearly the same with condenser temperature values higher than that of ambient values, due to the extra heat in the desorbed water refrigerant in the condenser.

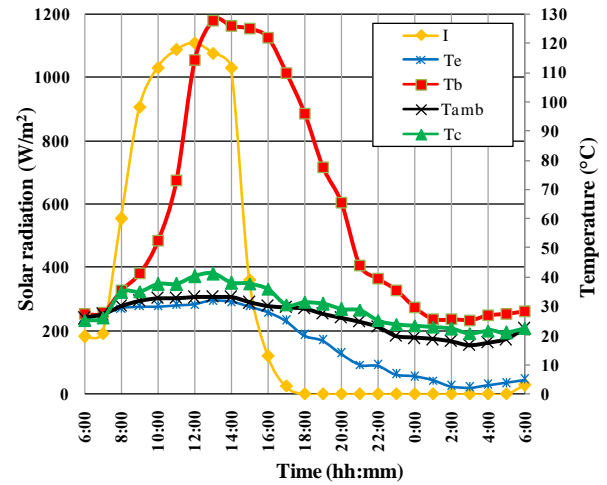


Fig.3 SAR with SGC1 temperature and solar intensity profiles on 19 Sep. 2021.

Moreover, the daily average variation of solar radiation intensity and adsorption bed, evaporator, condenser, and ambient temperatures of SAR when using composite adsorbents SGC2 of 90wt% silica gel powder and 10wt% activated carbon powder, with water as a refrigerant on 21 Sep. 2021, is illustrated in Figure 4. The maximum solar radiation intensity of 1091 W/m² is available at noontime. Thereafter the amount of available solar radiation intensity decreases till the end of the test. The adsorption bed temperature reached its maximum value of 126 °C at 2:00 p.m then it is reduced gradually, due to water desorption from the heated adsorption bed. While the evaporator temperature reached its lowest value of 3.2 °C at the end of the test at 6:00 a.m due to water adsorption in the cooled adsorption bed. Regarding the ambient and condenser temperatures, both profile trends are nearly the same with condenser temperature values higher than that of ambient values, due to the extra heat in the desorbed water refrigerant in the condenser. Despite SGC2 gave a higher adsorption bed temperature compared with SGC1, SGC2 produced a lower evaporator temperature due to the delay in desorption and adsorption of water in SGC2. Therefore, SGC1 conducted better performance compared with using SGC2. This may be attributed to the extra quantity of activated carbon on the composite adsorbent SGC2.

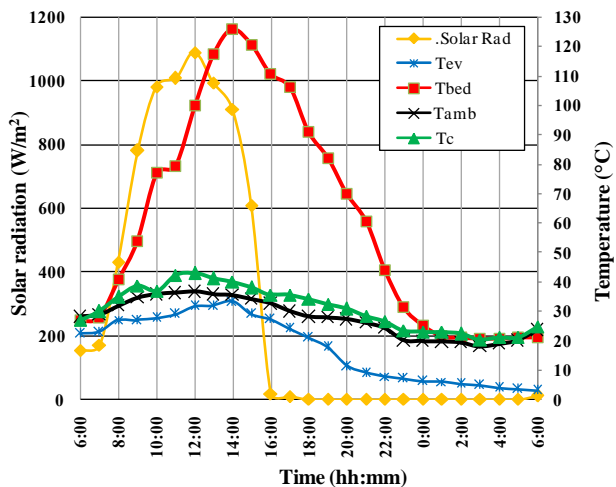


Fig.4 SAR with SGC2 temperature and solar intensity profiles on 21 Sep. 2021.

As can be shown in Fig. 5, the average COP of proposed SAR when using SGC1 and SGC2 with a comparison of Liu et. al. [13]. As illustrated in the mentioned figure, using SGC1 gives a higher COP value of 0.174 than that for SGC2 of 0.131 due to the ability of SGC1 to adsorb and desorb more water refrigerant, while COP of using pure silica gel as an adsorbent in Liu et. al. [13] system gives the highest value of 0.256.

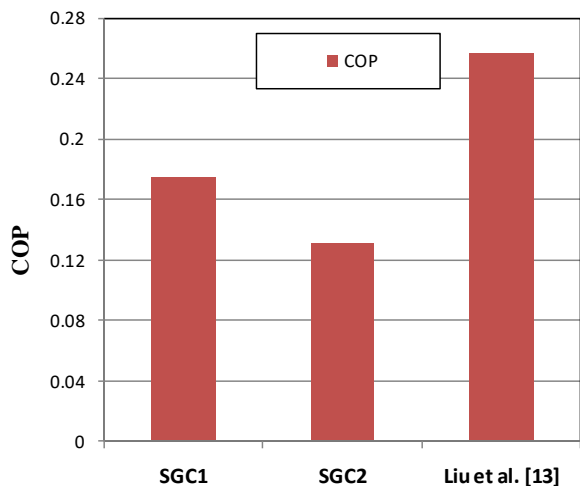


Fig.5 Comparison of the daily average COP for the proposed SAR with Liu et al. [13].

Figure 6 presents a comparison between the values of SCP when using SGC1, SGC2 and pure silica gel of Liu et. al. [13]. The illustrated data showed that the proposed system with SGC1 produced the highest value of SCP of 19.89 W/kg_{ads} among the compared values of 13.21 W/kg_{ads} for

SGC2 and of 8.13 W/kg_{ads} for pure silica gel of Liu et. al. [13].

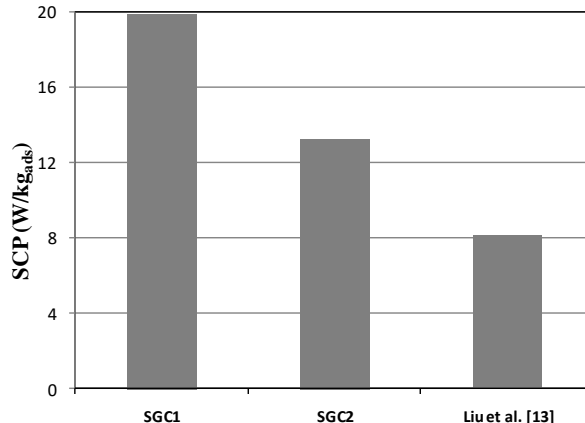


Fig.6 Comparison of the SCP for the proposed SAR with Liu et al. [13].

4 Conclusion

The main purpose of this work is to develop a solar adsorption refrigeration apparatus for cold production, and accommodate with the hot climate and arid regions in Upper Egypt. The effect of weather conditions of Qena City on the performance of the tested solar adsorption refrigerator equipped with two new composite adsorbents of SGC1, and SGC2 with water refrigerant is carried out. The reported outcomes can be summarized as:

- SGC1 gives better temperatures performance than SGC2 under the same conditions.
- The average value of COP under using SGC1 reached about 0.174 higher than 0.131 of SGC2.
- Comparing SCP under using SGC1 and SGC2 with pure silica gel in open literature indicated better values especially for SGC1.
- Using SGC1 is preferred as an adsorbent for SAR under harsh climates.
- The proposed new composite adsorbents are beneficial for storing vegetables and fruit in remote and rural areas where electrical power sources are insufficient or unavailable.

Authors' Contributions:

Ahmed Nagah Shmroukh (Conceptualization, Resources, Data collection, Writing – original draft, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing).

Essam Hares (Formal analysis, Supporting, Materials acquisition, Writing – review & editing).

Osama Hamdy (Formal analysis, Supporting, Software, Validation, Writing – review & editing).

Mostafa Abouelsoud (Data collection, Formal analysis, Conceptualization, Methodology, Writing – review & editing).

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