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Investigation of Air Solar Collector with Energy Storage for Domestic Purposes

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ABSTRACT

In the current study, a three-pass solar air collector (SAC) connected with a stone storage bed is investigated. The thermal energy storage was used to store energy during the day time and then re-use it at night or during the cloudy hours. Four solar air collectors were used in this research which were connected consecutively to the stone storage bed. High density black stones (440 kg) of different sizes and weights were used as a storing medium. The physical properties of the stones were measured in the lab. The experiments were conducted on clear and partly cloudy days for three random days at a constant air flow rate (0.0377 kg/s) for the climate of the Dohuk city, Iraq. The parameters that affect the thermal performance of (SAC) were evaluated with integration of the stone storage bed. The solar radiation intensity, air temperatures at different locations were measured. Obtained data showed that the stone storage bed gives a temperature difference of about 10°C after sunset and lasts for about 4-5 hours. The used stone bed has the property of acquiring stored heat for a long time after sunset which was released at night or on partly cloudy days.

KEY WORDS: Solar air collector (SAC), Energy storage, Stone storage bed, Stone (rock).

1. INTRODUCTION

Solar energy is becoming one of the most widely used renewable energy sources, with the advantages of the sun's sources (heat and light) being converted into electrical energy and also having thermal applications. In term of solar thermal energy systems, solar air heaters (SAHs) play a significant role which used in a wide range of contexts, such as heating houses with hot air in the winter and drying agricultural goods[1]. When there is no solar radiation, using solar energy in applications such as heating or drying processes may pose significant difficulty. As a result, it has been proposed to employ the energy storage system supplied by stones to encounter energy consumption at nighttime or through cloudy days. There are several methods for storing thermal energy such as, sensible heat storage, latent heat storage, chemical energy storage, etc. [2]. Solar energy was converted into thermal energy by the solar collector. Solar collectors capture direct sunlight and turn it into thermal energy, which can be stored as sensible heat, latent heat, or a mix of the two form of heat [3]. Investigated both experimentally and theoretically a built-in solar heater for the rock bed. A pyranometer set on a shadowing platform was used to measure total sun radiation hourly. When it was tilted at a 47° angle, it was discovered that it has a maximum of 46% storing efficacy. The temperatures of the entry and output air, the temperature of the bed, the temperature of the surrounding environment, and the sun insolation were all measured. [4]. Kürklü A, et al. [5] a study was conducted to see if solar energy might be stored under the earth in a stone layer for conservatory heat. Tests were conducted in two similar polyethylene channel greenhouses, each with a ground surface of 15 m2. Backfilled rocks in two ditches were isolated in the soil in one of the greenhouses. When the need for energy storage or release was necessary, a centripetal fan with a 1100 m^3/h air flow rate forced greenhouse air through the rock-bed, which was regulated and controlled by two thermostats. The vents were kept covered until there was a greater condensation event inside. According to the findings of that study, the stone bed system caused a nighttime air temperature differential of roughly 10 °C among both greenhouses. Hänchen M et al. [6] studied proposes an experimentally proven numerical heat transport model of packed rocks on air base. Heat losses via the walls was taken into consideration in that model. It evaluated the thermal efficiency of charging and dis charging operations, including the energy associated cost of pumping effort. When doing a parametric analysis of the length of the packed bed, the fluid flow rate is taken into consideration, the diameter of particle, and the unlike solid phase materials, the continuous 24-hour functioning of a thermal storage unit used in a distinctive solar current power plant is simulated using an optimal design. A packed bed of rocks was used as the storing medium in the thermal energy storage device and air as the high-temperature heat transfer fluid that was researched by Zanganeh G, et al. [7]. Concentrated solar power (CSP) uses have been investigated. A 6.5 MWh pilot-scale thermal storage device was created and was experimentally proven to generate thermoclines. It was buried underground and had a truncated conical shape. It has been verified by experience. The model unit was then used to enterprise and simulate an array of two industrial-scale thermal storage units, each with a capacity of 7.2 GWh. Another study by Barton NG. [8] calculated thermal energy storage in the loosely packed rock bed of air-blown thermal energy (not tightly closed). Thermodynamic energy from the sun storing for power production or process heating was an important application. The fluctuation of density with temperature was accounted for in a new formula for single dimension air flow through the rock bed. The model equations were numerically solved, and their influences and factors such as particle dimension, bed deepness, and air speed were reported. It had been demonstrated that charging the rock bed with downhill air speed and discharging it with upwards airflow was beneficial. These rocks collect heat energy from the sun's rays during the day and then reuse it after nightfall or in cases where the weather was cloudy at a steady temperature and high storage density. Singh PL, et al. [9] proved experimentally that the packed bed solar heat storage system's thermal performance was investigated for several months under various solar and ambient conditions. Rock pebbles weighing 8500 kg were placed in the insulated packed bed heat storage unit. The heat storage system's solar collection and heat retrieval efficiency ranged between 36–51% and 75–77%, consecutively. When compared to a filled bed occupied with phase change material (PCM), the created packed bed's heat retrieval efficiency was shown to be higher. Experiments showed that the heat generated from the packed bed and the heat generated from the hot air that came from the bed were close to what was expected. Ghoreishi-Madiseh SA, et al [10] proposed that the sustainability of seasonal waste heat storage in rock heaps for a colder temperature rural off-grid village that relies entirely on diesel generators to provide electricity. During the winter, the community directly uses the recovered waste heat from the diesel generators. Unlike most research in the sector, which focuses on solar energy applications, the new method of channeling the exhaust of diesel generator sets through a rock pile during the summer may generate a seasonal waste heat storage (SWHS) that may help the municipal for space heating throughout the winter season. C. Choudhury, et al. [11] found that the charging time (θ), rock bed size (flow length, H), cross-sectional area for square cross section (AR), rock size (DR), air mass velocity per unit bed cross-sectional area (G), and void fraction (ϵ) of a rock bed thermal energy storage device were coupled to a two-pass solar air heater. The development was achieved for the winter season environments in Delhi by examining the parameter effects of the energy storage and the fee per unit of energy stored in the rock bed. It was then concluded that the ideal charging period for the rock bed storage unit with a double pass solar air heater is 8 hours, from 8 a.m. to 4 p.m. During charging, bed porosity and rock size had little effect on cost or performance. Moreover, J. Pascal coutie, et al.[12] proposed that curves and empirical equations could be used to represent the study's findings. Following that, two applications of this theoretical model were examined. One was the development of a novel volumetric convective heat transfer coefficient estimation method based on the comparison of theoretical modeling and experimental data. The second application was a design approach for solar rock-bed storage applications that involves determining optimal values for characteristics like air velocity, particle diameter, and the storage unit's geometrical elements. This study examines the performance of a triple-pass solar air heater with a storage bed unit. The stone materials were employed as a kind of storage. The charging and discharging trials that were carried out in the city of Dohuk, Iraq, in December 2021, January and February 2022 were affected by the city's climate.

2. EXPERIMENTAL SET-UP

In the current study, a solar air collector (SAC) with energy storage was designed and installed. The purpose of current study is to examine and improve the thermal performance of the solar air heater and storage system. The experimental test rig was installed on the top of building in Duhok city, Iraqi. Four solar air collectors were installed for the purpose of this study. The characteristics of the solar air collectors are illustrated in Table 1. Each solar collector unit is (90 x 55 x 7.5) cm and was placed on a steel base with an inclination angle of 55° (the optimum angle in winter for Dohuk City) [13]. The unit was directed to the south. All solar air collectors were connected to each other by a 4 inches diameter PVC pipe. The PVC pipe was wrapped with glass wool thermal conductivity (k= 0.034 W/m^2) to reduce heat losses to the atmosphere. Also, the back and the walls of the solar air collectors were insulated by using glass wool too. This also helped keeping heat from escaping into the outside atmosphere. Figures 1(a & b), and 2 illustrate a schematic design of a solar air collector with, a stone bed for storing. The stones (black, high-density) were put into very well insulated thermal storage. Figure 3 shows a cross-sectional view of the stone bed storage. All fittings were made of rustproof and durable stainless steel and aluminum. The storage container was made of mild steel plate which enveloped by 60mm polyurethane insulation foam. This give an excellent heat storage capability even at low outside temperatures. The internal dimensions of the storage were L/W/H: (935 x 520 x 690) mm, or a volume of 0. 0.335478 m^3.

Air from the (SAC) is sucked by a fan with a diameter of (96 mm) into the storage. The air mass flow rate was controllable at a range between 1 and 9.5 m/s and the fan consumed 40 W of power. The purpose of the fan was to force the air through the stone bed to gain heat and then send it out to the required heated space. Sixteen K-type calibrated thermocouples were used to measure temperatures. The thermocouple was placed on the collector glass to measure the temperature of the collector. The temperature was measured at the air gap (bottom, middle, and top) solar air collector. Two thermocouples were placed at the entry and exit points of the (SAC). The temperatures inside the storage stone bed were measured at different heights (bottom, middle, and top) by means of a thermocouple. The storage bed's inlet and outlet temperatures were also measured. The brand of the solar power meter device was TES 132. The HP-866B device was used to measure the air speed at the outlet storage stone bed. Also, NAPUI 130D data logger with 16 input channels was used to record temperatures. All measurement instrument accuracy is listed in Table 2. All three devices were sat up to record the data every 30 minutes intervals.

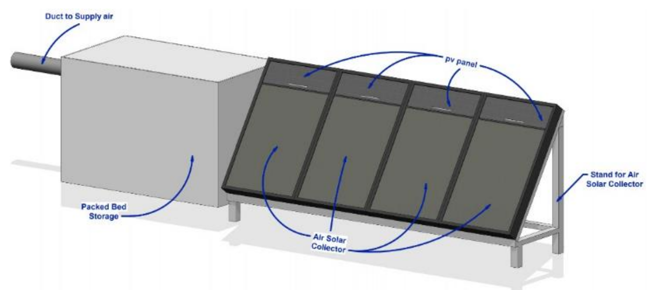


Figure. 1a. A schematic illustration of the solar air collector with a stone storage bed for the front view.

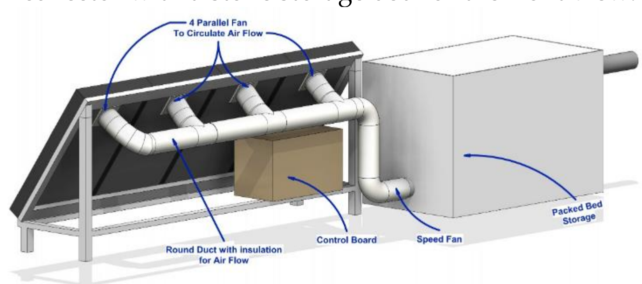


Figure 1b. A schematic illustration of the solar air collector with a rear view of the stone storage bed.

Figure. 2. A photograph of the triple-pass solar air collector with a stone storage bed

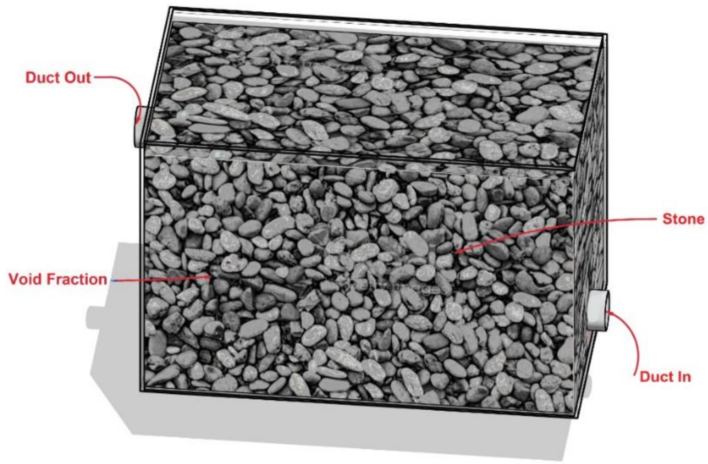


Figure. 3. An interior appearance of the stone storage bed

TABLE 1: Solar air collector properties and components

No.	Descript ion	Material	Qty	Size (mm)	Remark
1	Aluminum frame	Alu. 6063-T5	1	1050	black coat
2	Solar panels	polycrystalline	1	460x125	8 Watt
3	Alu. frame inlet	Alu. 6063-T5	1	660	black
4	Galvanized sheet	Alu.	1	623x600	black
5	Glass	Brown glass	1	857x609	brown transparent
6	Fan	PVC	1	92x92x21	Up to 85m^3/h

TABLE 2. Instrument accuracies

Instrument	Accuracy	Range
Data logger (NAPUI 130D)	± (0.5 % + 0.6 °C)	-100 °C to 1370 °C
Pyranometers (TES 132 solar power meter)	± 0.7	0 W/m^2 to 2000 W/m^2
K-type thermocouple	± 0.4	-100 to 1200 °C
Anemometer (air flow velocity)	± 5%	0.2995 m/s to 29.996 m/s

3. THERMAL PERFORMANCE EVALUATION

The stone density was measured in the lab and the average was 2660 kg/m^3. In order to calculate the heat transfer rate, convection heat transfer coefficient and void fraction, it was proposed that the stone was considered as a sphere with a diameter (D). equation (1) is the most used empirical formula to estimate the diameter of the stone [14]. Void fraction (ε) is calculated by using equation (2). Table (3) shows the physical properties of the stone used in the heat storage.

Where the spherical stones diameter (D_S) is:

$$D_s = \sqrt[3]{\frac{6\,M}{\pi n \rho_s}} \quad (1)$$

calculating the void fraction (ϵ) include the following equation [15]:

$$\varepsilon = \frac{V_I - V_m}{V_I} \quad (2)$$

Table 3 physical properties of the stone bed and the air used in the experiment.

Equivalent diameter (measured)	69 mm
Specific heat of the stone (in accordance with [16]).	710 J/kg
density of the rocks (measured)	2660 kg/m^3
Specific heat of the Air	1.005 kJ/kg K
Mass flow rate of Air	0.0377 kg/s
Total weight of the rocks (measured)	442 kg
Number of rocks (measured)	960
ε, void fraction (measured)	0.4

3.1 EFFICIENCY OF ENERGY COLLECTION AND RECOVERY (η)

The solar energy collected (QC) and energy recovered (Qrc) were calculated using the following equations:

$$Qc = \dot{m}\, C_p \; (T_{out} - T_{in}) \qquad (3)$$

$$Qrc = \dot{m}\, C_p \; (T_{in} - T_{out}) \qquad (4)$$

The following formulae were used to calculate the collected and recovered energy efficiency respectively [5]:

$$\eta_c = \frac{\int_{t1}^{t2} Q_c dt}{\int_{t1}^{t2} IAdt} \quad \text{(Hourly)} \qquad (5)$$

$$\eta_{rc} = \frac{\int_{t1}^{t2} Q_{rc} dt}{\int_{t1}^{t2} Q_c dt} \quad \text{(Hourly)} \qquad (6)$$

During the calculations, the heat lost to the atmosphere due to good insulation was not calculated.

3.2 Mass Flow Rate (ṁ).

This formula can be used to calculate the mass flow rate of air (ṁ).

$$\dot{m}_{air} = \rho_{air} \, A \, V_{air} \qquad (7)$$

3.3 STONE SURFACE HEAT-TRANSFER COEFFICIENT DETERMINATION

The effective thermal conductivity is often estimated in energy equations using correlations that have been discovered empirically. In the literature, there are a number of heat-transfer correlations that may be used to determine the temperature distribution of the system. Heat-transfer coefficient which was developed by [17].

$$h = \frac{700}{6(1-\varepsilon)} G^{0.76} D_r^{0.24} \qquad (8)$$

G the superficial mass flow rate, or air mass flux [18], is defined as:

$$G = \frac{\dot{m}}{A_{bed}} \qquad (9)$$

Clark (1986) posits a relationship between the heat-transfer coefficient h and the Reynolds number (10–10,000) for air flow through a bed of randomly packed spheres [18].

$$\frac{h\, D_r}{K} = 2 + 1.354 Re_o^{0.5} Pr^{1/3} + 0.0326 Re_o Pr^{0.5} \qquad (10)$$

where Reynolds (Reo) and Prandtl (Pr) numbers, as stated below, are represented:

$$Reo = \frac{D_r G}{\mu}, \; Pr = \frac{\mu C_p}{K} \qquad (11)$$

3.4 TEMPERATURE MEASUREMENT UNCERTAINTY ACCURACY CALCULATION

The root-sum-square Eq. (12 &13) method was used to calculate the overall uncertainty. Because the total uncertainties for the K thermocouple are less than 0.42 °C, the random error is too tiny to have an impact on the overall uncertainty value [19].

$$u = T_{measured} - T_{drift} \qquad (12)$$

where: -

u is the uncertainty

$T_{measured}$ is the temperature for thermocouples (°C)

T_{drift} is the temperature measured is changing (°C).

$$u_{total} = \sqrt{u_{coll.}{}^2 + u_{amb.}{}^2 + u_{in.sto.}{}^2 + u_{out.sto.}{}^2} \qquad (13)$$

where: -

$u_{coll.}$ is the uncertainty temperature for thermocouples for collector (°C).
$u_{amb.}$ is the uncertainty temperature for thermocouples for ambient (°C).
$u_{in.sto.}$ is the uncertainty temperature for thermocouples for inlet to storage (°C).
$u_{out.sto.}$ is the uncertainty temperature for thermocouples for outlet to storage (°C).

4. RESULTS OF EXPERIMENTS

An experimental study was conducted to evaluate the heat performance results of a three-pass solar air heater with a storage stone bed. The tests were conducted for three months on clear and partly cloudy sky days with a steady air flow rate (0.0377 kg/s). The experimental tests for three days were randomly selected on the15th of Des. 2021, 9th of Jan and 14th of Feb. 2022 for Dohuk city, Iraq.

The relationship between solar radiation intensity, air outlet temperature from the solar air collector, and the ambient temperature versus time are shown in Figure 4. The temperature trends of the inlet (ambient temperature) and increase in the outlet of the solar air collector are almost similar with a change in the intensity of solar radiation, as well as a difference between the outlet temperatures of the solar air collector and the ambient temperature for three different days over time, where different values are obtained with the variation of the day time (daytime duration).

The values on Feb 14th, 2022 were the highest in the outlet temperatures of the solar air collector due to the high solar radiation intensity and a slight rise in the ambient temperature. As the intensity of the solar radiation increases from 550 W/m² at 9:00 A.M. until it reaches its peak of 1080 W/m² at 11:30 A.M. - 12:30 P.M., the outlet temperature of the solar collector also increases until it reached 51.8 °C. After the solar radiation intensity reaches its peak, the temperatures coming out of the solar air collector began to gradually decrease with the decrease in the intensity of solar radiation, reaching the lowest level at 17:00 P.M. when the sun set. The ambient temperature ranged from the morning to the evening, between 9 and 21°C. In the mid-day, the temperature difference (ΔT) between the outlet (from the solar air collector) and the inlet (ambient temperatures) was about 31°C.

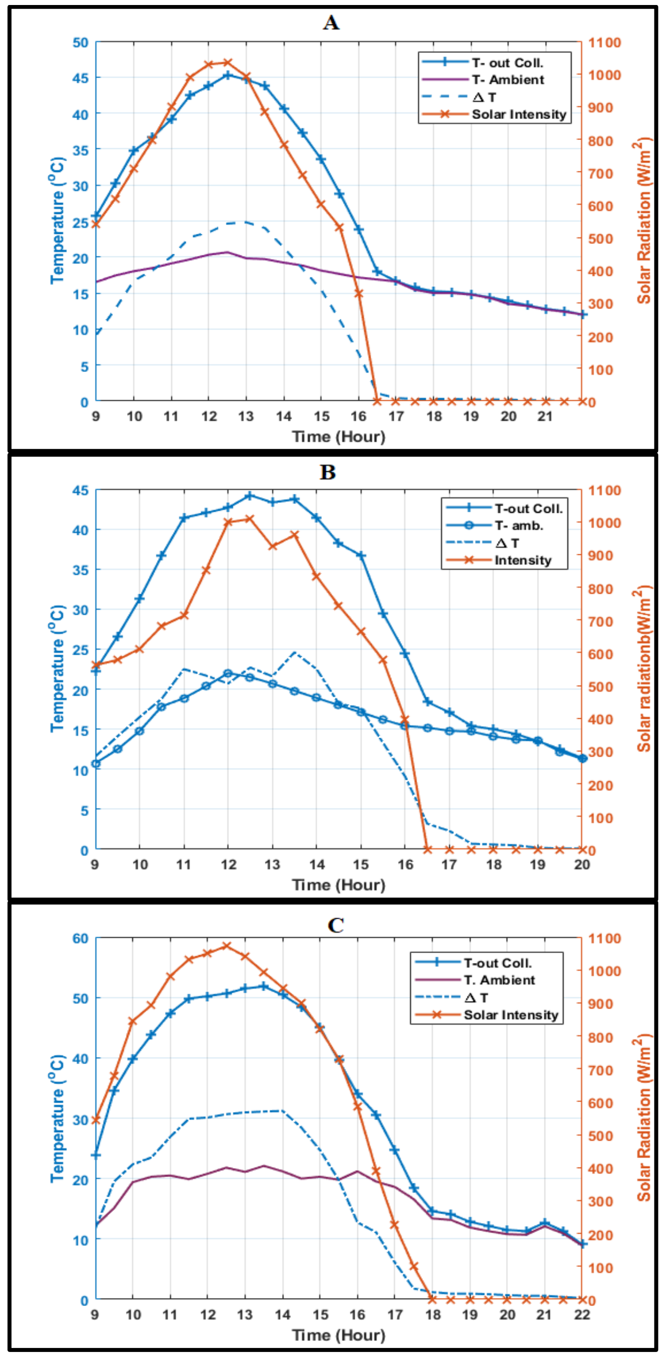
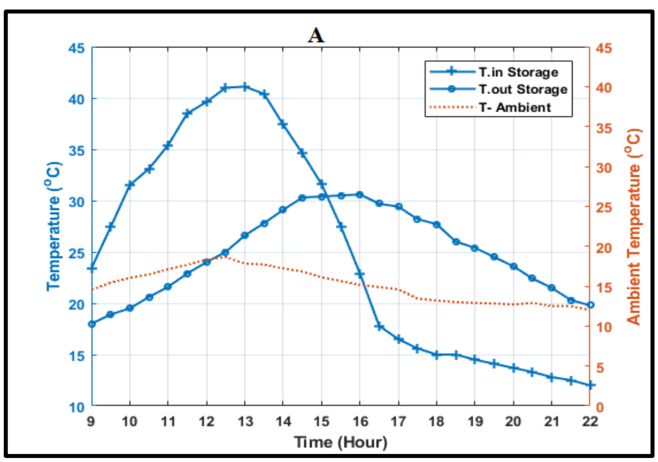


Fig 4. Hourly temperature rises of the (inlet & outlet) solar air collector with solar radiation intensity for

days: (A) Dec. 15th, 2021; (B) Jan. 9th, 2022, (C) Feb. 14th, 2022.

The temperatures of the air outlet from the solar air collector to the stone storage bed and the air outlet from the storage bed, as well as the ambient temperature against time for different three days are illustrated in Figure **5**. The figure shows that inlet temperatures increase with the increase in the intensity of solar radiation over time. It has also been observed that the temperature of the air outlet from a stone storage bed increased gradually over time due to the presence of pebbles inside the storage bed, as these pebbles gain heat during the day to charge the storage bed. In contrast, the behavior of the ambient temperature is almost the same with little change all days under investigation.

Maximum temperature values were obtained on the Feb 14th, 2022, due to the high intensity of solar radiation which reached 1080 (W/m^2) at 12:30 P.M., as well as a small increase in ambient temperatures. After the sunset, the temperature outlet of the stone storage bed was found to be between 38.4 °C and 30 °C at 16:30 –19:00 P.M., while the ambient temperature was 19.5 °C to 11.9 °C at the same time interval. Therefore, longer hours were obtained for the discharging period until it reached 22:00 P.M., where the temperature outlet from the stone storage bed was 20 °C while the ambient temperature was 10 °C, meaning that the temperature difference (ΔT) was 10 °C.



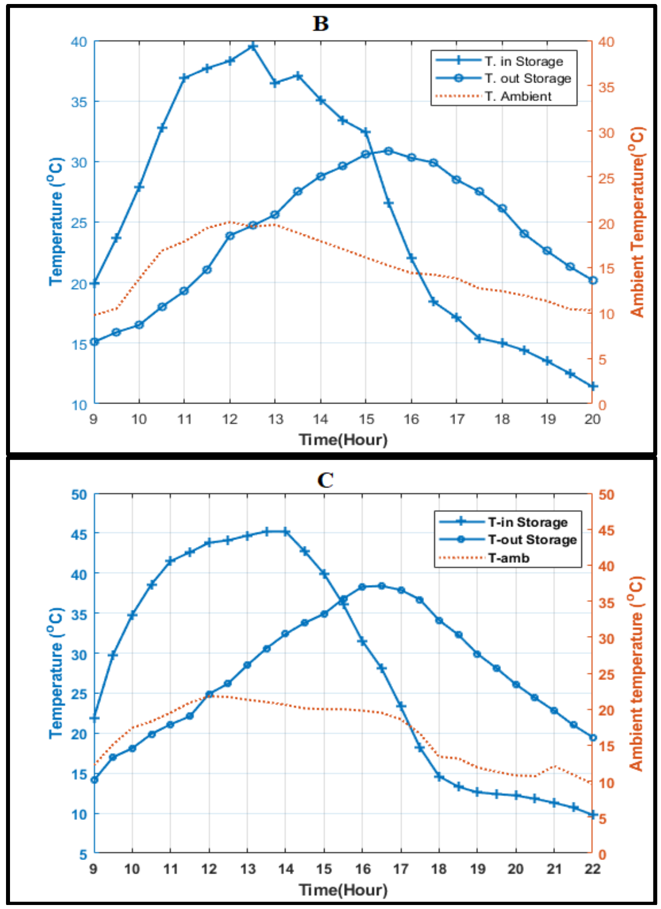


Figure 5. Hourly temperature rises of the (T-in & T-out) of storage stone bed and ambient temperature for the days: (A) Dec. 15th, 2021, (B) Jan. 9th, 2022, (C) Feb. 14th, 2022.

The temperature change within the stone storage bed layers at three points were measured. Bottom, middle, and upper (three elevations) against time for three different days are shown in Figure 6 The temperature of the air coming out of the solar air collector enters at the bottom of the stone storage bed. The figure shows that the temperature of the heat-absorbing layers of stone increases with time and then rises to its maximum value at noon. It has been observed that the layers of the stone need a time of about 2 hours to absorb the heat gained and then start to supply the hot air during the charging process. Before the sunset, the process of discharge begins. It had been observed that the temperatures of the lower layer began to decrease gradually due to the decreased in the intensity of solar radiation. It was observed that the air coming out of the heat storage supplies air with high temperatures after sunset. This is occurred as a result of accumulation of heat between all layers of the stone bed.

Higher storage results were obtained on the Feb 14th, 2022, due to obtaining high energy from the solar air collector into the storage bed. It was noted that the amount of thermal energy absorbed by the stone during the charging process was between 11:00 A.M. and 16:00 P.M. as the temperature of the air entering the storage bed reaches about 35 °C to 44°C. During the discharged process, the maximum air temperature was 38.1 °C at 16:00 p.m. After the sunset, the air was discharged for 6.5 hours with a difference (ΔT) of 10 °C until 22:00 P.M.

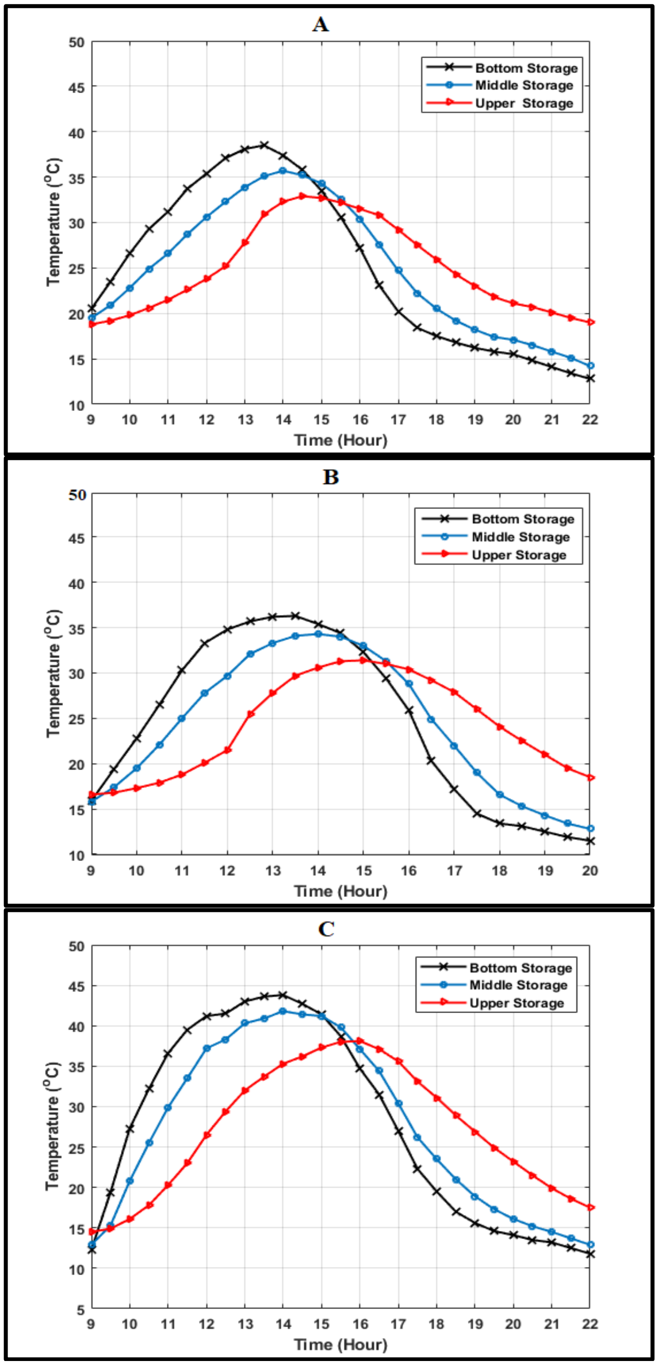


Figure 6. Hourly temperature rises of the (Bottom, Middle, and Upper) storage stone bed layers for days: (A) Dec. 15th, 2021; (B) Jan. 9th, 2022, (C) Feb. 14th, 2022.

5. Conclusion

The main parameters and performance of a three-pass solar air collector accompanied with a stone storage bed was measured and evaluated. High density black stones were used as a storing medium for the thermal energy collected. Obtained results showed that thus material has good potential for energy conservation as it can supply hot air with about 10 °C higher than the ambient temperature for about 4-5 hours after sun set. Thus, system seems to be a suitable economic one in Iraq since it is cheap, available and environment friend.

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APPENDIX

Nomenclatures			
Ds	Diameter stone (m)	T_{in}	Temperature inlet (°C)
M	Mass of stones (kg)	T_{out}	Temperature outlet (°C)
n	number of the particles	I	solar radiation measured (W/m^2)
ρ_s	stone density, (kg/m^3)	A	area (m^2)
ρ_a	air density, (kg/m^3)	A_{bed}	bed's cross-section, (m^2)
ε	void fraction	η	Efficiency (%)
V_I	total bed volume (m^3)	h	stone surface heat-transfer coefficient (W/m^2 K)
V_m	material volume in a packed bed (m^3)	G	superficial mass flow rate (kg/m^2. s)
V_{air}	air speed (m/s)	K	thermal conductivity, (W/m K)
Q_C	heat energy of solar collector (W)	μ	the viscosity, (kg/m. s)
Q_{rc}	heat energy of recovery (W)	Reo	Reynolds number
V	bulk volume	Pr	Prandtl number
ṁ	mass flow rate (kg/s)		
C_p	specific heat (kJ/kg °C)		