

SOLAR THERMOCHEMICAL ENERGY-STORAGE SYSTEM (THERMOCHEMICAL BATTERY)

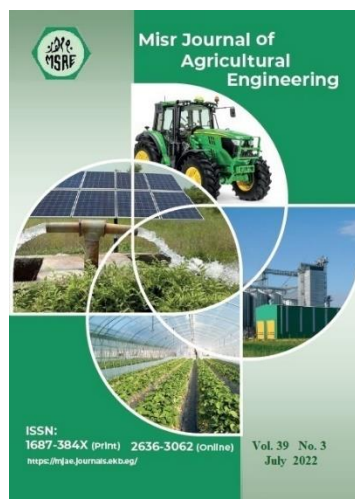
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Solar energy; Energy storage; Thermochemical battery.

ABSTRACT

This work aimed to investigate the potential of direct storage and restoration of solar energy in a chemical form and to construct a portable, rechargeable, and usable solar thermochemical battery for agricultural applications. Many attempts were conducted to select a suitable thermochemical storage material (TCM) among which are self-indicating silica gel (blue/pink), commercial white silica gel, and natural zeolite. During the experiments, moist TCMs samples were dried (energy-charged) by a one square-meter stainless-steel parabolic solar energy concentrator in three experimental configurations. An experimental aluminum thermochemical battery size 35 × 35 × 5 cm filled with 3.5 kg of TCMs working as a heat-exchanger and a portable energy charging/discharging thermal battery was evaluated. Energy restoration (discharging) was achieved by applying forced humid air generated from an ultrasonic mist generator and an air-circulation fan through a set of perforated pipes located inside the thermochemical battery. Results showed that TCM self-indicating silica gel was able to store 165 Wh/kg of solar energy at the charging process compared to natural zeolite (124 Wh/kg) and white-silica gel (80 Wh/kg). The energy discharging efficiency of the self-indicating silica gel was 57.7%, while the efficiency of the natural zeolite and white silica gel was 45.8% and 39%, respectively. Direct storage and use of solar energy in a thermochemical (TCM) form can reduce costs and maintenance of renewable energy applications compared to the high-cost photovoltaic systems. TCMs thermochemical batteries, like traditional electrical batteries, can act as energy master-key for different agricultural applications, as well as in thermo-sensitive processing and treatment.

1. INTRODUCTION

Energy is the biggest concern in economies, industries, and food production chains. As the agricultural production elements and chains are energy-intensive processes, energy costs are affecting access for low-income consumers (Brown et al., 2015). Rising energy prices and evolving policies promoting renewable energy and on-farm conservation

practices have reformed the relationship between the energy and agriculture sectors (Beckman et al., 2013). Traditionally, agriculture used energy both directly in the form of fuel and electricity and indirectly using energy-intensive inputs, such as fertilizers and pesticides. Hence, innovative systems for shielding and enhancing natural resources based on increasing productivity are needed. Because solar energy is a variable and intermittent source of energy that can fluctuate a lot in nature due to clouds and weather variations, developing reliable storage systems for smooth and stable operations under fluctuating solar irradiation conditions is extremely important (André and Abanades, 2020).

The thermal energy storage (TES) systems as a potential solution for storing energy for low- and medium-temperature applications, and to balance energy supply and demands have been recommended throughout different investigations (Yan et al., 2020; Desai et al., 2021; and Gil et al., 2010). The active storage system stores thermal energy directly to the storage media through the forced convection process. The storage medium circulates through a solar collector or a heat source. Whereas, in the passive storage system, the heat transfer fluid exchanges energy through a still storage medium. Airò Farulla et al. (2020) agreed with Zhang et al. (2016) that thermochemical systems combined with heating systems have an increasing involvement in production systems for their better performance in comparison with sensible and latent heat storage technologies, especially for energy storage time dynamics and capacity. AuYeung and Kreider (2017) added that thermochemical storage has inherently higher energy density than latent heat storage because, in addition to sensible heat, energy is stored as chemical potential without any need for exceptional storage arrangements. In comparison with sensible heat storage, Dincer and Ezan (2018a; 2018b) mentioned that the thermochemical energy storage method can provide nearly ten times higher storage density. Aydin et al. (2015) agreed with Kousksou et al. (2014) that TCEs have the highest theoretical energy capacity ($0.4 - 3 \text{ GJ}/\text{m}^3$) compared with sensible heat storage (SHS) ($0.2 \text{ GJ}/\text{m}^3$), and latent heat storage (LHS) ($0.3 - 0.5 \text{ GJ}/\text{m}^3$), and the heat losses can be practically negligible.

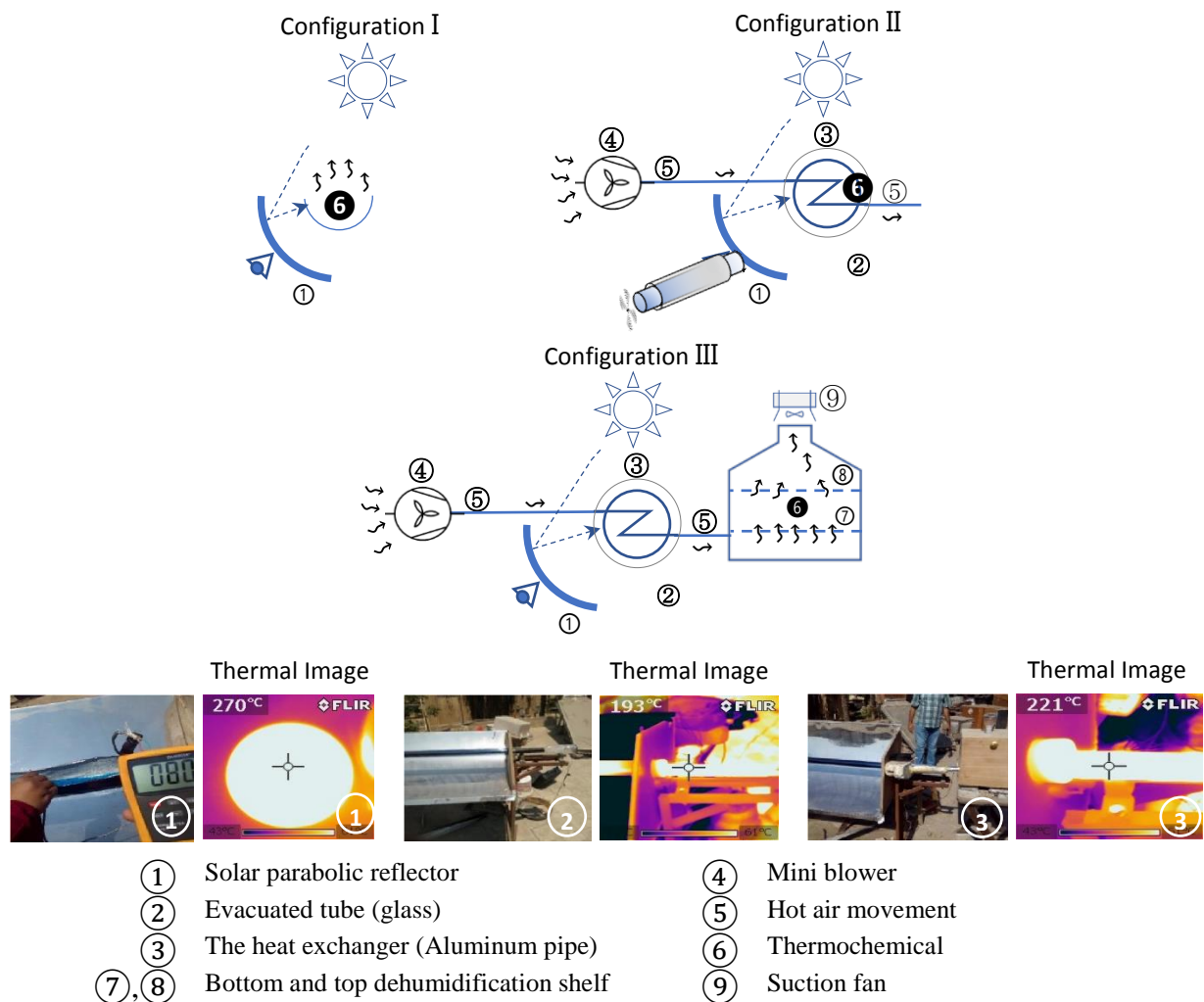
Wu and Long (2015) listed the thermal energy storage methods in three categories: Ⓐ sensible TES system (SHS), stores energy through a temperature change of storage mediums; Ⓑ Latent TES phase-change energy storage (LHS), which stores heat through phase transformation of phase-change materials (PCMs); and Ⓒ Thermochemical storage, principally (TCE) supported a reversible reaction.

Wang et al. (2020) explained the main difference between sensible heat storage systems and latent heat storage systems, and they indicated that a thermochemical heat storage system uses reversible endothermic/exothermic reactions to charge, store and discharge energy between solar heat and chemical reactants. Therefore, this work aims to investigate the potential of direct storage and restoration of solar energy in a chemical form and to construct a portable, rechargeable, and usable solar energy cell called the thermochemical battery for various agricultural applications.

2. MATERIALS AND METHODS

Several experimental trials were conducted at the Solar Energy Lab., Fac. of Agric., Ain-Shams Univ., Egypt to select a suitable thermochemical storage material (TCM) among self-indicating silica gel (blue/pink), commercial white silica gel, and natural zeolite. During experiments, humid TCMs samples were dried (energy-charged) by a one square meter stainless-steel parabolic solar collector in three experimental configurations: samples were

charged in (I) an aluminum semicircle tray located at the reflector focal axis (Figure 1, config. I), (II) an open-ends aluminum tube placed at the center of an evacuated Pyrex-glass tube at the focal axis of the reflector and a five volts fan was placed at one end of the aluminum sample tube to extract moist air at 1.25 m/s from the heated sample (Figure 1, config. II), and (III) a dehumidification chamber connected at one end to an open-ends empty aluminum tube placed in evacuated Pyrex-glass tube located at the focal axis of the reflector (Figure 1, config. III). A solar chimney with a five volts fan above the dehumidification chamber extracts the moist air at 1.25 m/s from the samples. Figure 2 illustrates TCM charging in the dehumidification chamber process flow diagram. An experimental aluminum container (thermal battery) size $35 \times 35 \times 5 \text{ cm}$ filled with 3.5kg of TCMs worked as a heat-exchanger and a portable energy charging/discharging cell (i.e., a thermal battery) was evaluated by measurement and control set as shown in Figure 3.



Config. I Solar parabolic charging via the aluminum sheet,
 Config. II evacuated tube with solar parabolic trough collector, and
 Config. III evacuated tube connected with material box fixed in solar parabolic through collector

Figure 1. TCMs charging process (dehumidification) by three experimental configurations.

A configuration of programable temperature-humidity measurement and control unit illustrated in Figure 3 was used to restore thermal energy at a desired rate and level. The energy restoration process was achieved by applying forced humid air generated from an

ultrasonic mist generator (Figure 4) and an air-circulation fan through a set of perforated pipes located inside the thermochemical battery.

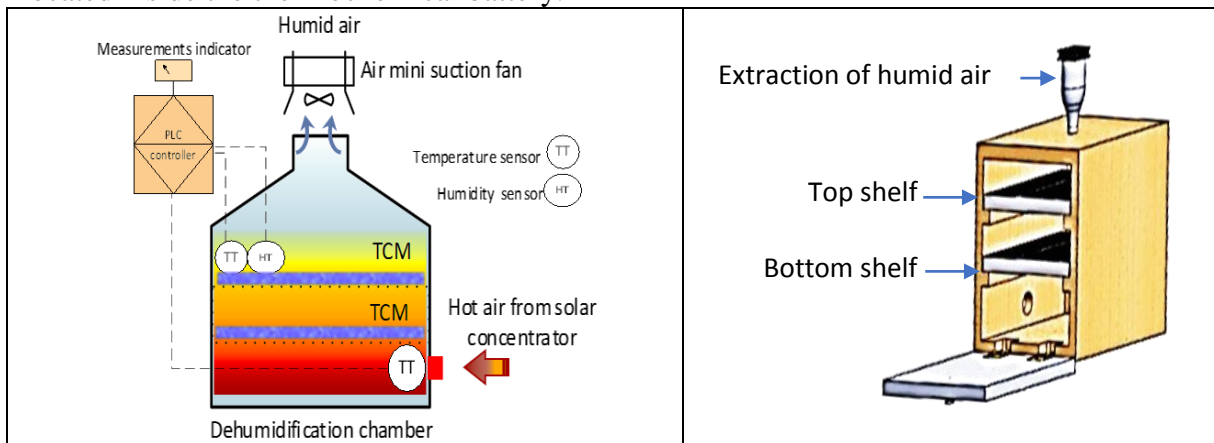
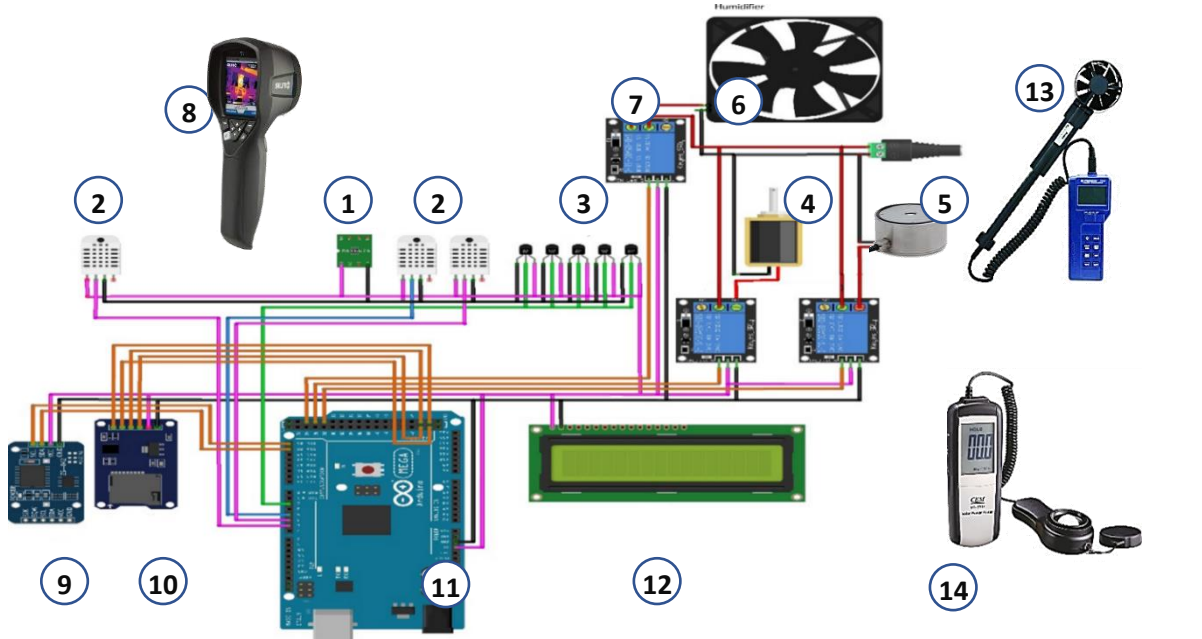


Figure 2. TCM battery charging process in dehumidification chamber top and bottom shelves.



Measurement & Control	device	resolution	range	unit	accuracy
Temperature	① max6675 (K)	0.25	0~ 700	°C	±1.5
Temperature	② RHT03	0.1	-40~ 80	°C	<0.5
Relative humidity	② RHT03	0.1	0~100	%	±2
Temperature	③ DS18B20	0.01	-55~+125	°C	±0.01
Water control	④ Solenoid valve				
Water atomizer	⑤ Ultrasonic				
Mini blower	⑥ Fan				
Power electronic switch	⑦ Relay (5v)				
Temperature	⑧ FLIR i7 thermal cam.	< 0.1°	-20~+250	°C	±2
Time	⑨ RTC (DS1307)				
Data storage	⑩ SD card module				
The programmable logical control	⑪ ATmega328P				
Measurement indicator	⑫ LCD				
Airspeed Anemometer	⑬ model 731A	0.01	0.00-30.00	m/s	±3%+0.1
Solar power	⑭ Solar power meter	1	1999	w/m ²	± 10

Figure 3. TCM battery measurement, control, and data logging unit.

Pramuang and Exell (2007) described the blue/pink silica gel as a good adsorbent at a relative humidity between 50% and 80% and illustrate the adsorption isotherm of water vapor on silica gel as seen in *Figure 5*. The energy analysis of the TCM battery was performed on charging ($Q_{\text{charged bat.}}$) and discharging ($Q_{\text{discharged bat.}}$) processes. Stored energy is the net energy gained from solar energy (Eq. (1)) after counting energy losses (Eqs. (2) and (3)) in TCM preheating (Eq. (4)), TCM cooling (Eq. (5)), and energy losses from battery wooden frame (Eqs.(6) and (7)) according to Abedin (2010); and Çengel and Ghajar (2015).

$$Q_{\text{solar}} = \dot{M}_{\text{air}} c_{p \text{ air}} (T_1 - T_2) \text{ and } \dot{M}_{\text{air}} = \frac{A \times V}{v} \tag{1}$$

$$Q_{\text{charged bat.}} = Q_{\text{solar}} - Q_{\text{losses}} \tag{2}$$

$$Q_{\text{charged bat.}} = Q_{\text{solar}} - (Q_{\text{bat. cooling}} + Q_{\text{bat. preheating}} + Q_{\text{bat. frame}}) \tag{3}$$

where M_{air} and $C_{p \text{ air}}$ are the mass and specific heat at a constant pressure of the air as working fluid ($kJ/kg \text{ } ^\circ C$), T_1, T_2 are the initial and final temperatures of the working fluid, V is airspeed (m/s), and v is the specific volume of the air (m^3/kg) (Eqs. (8):(12)).

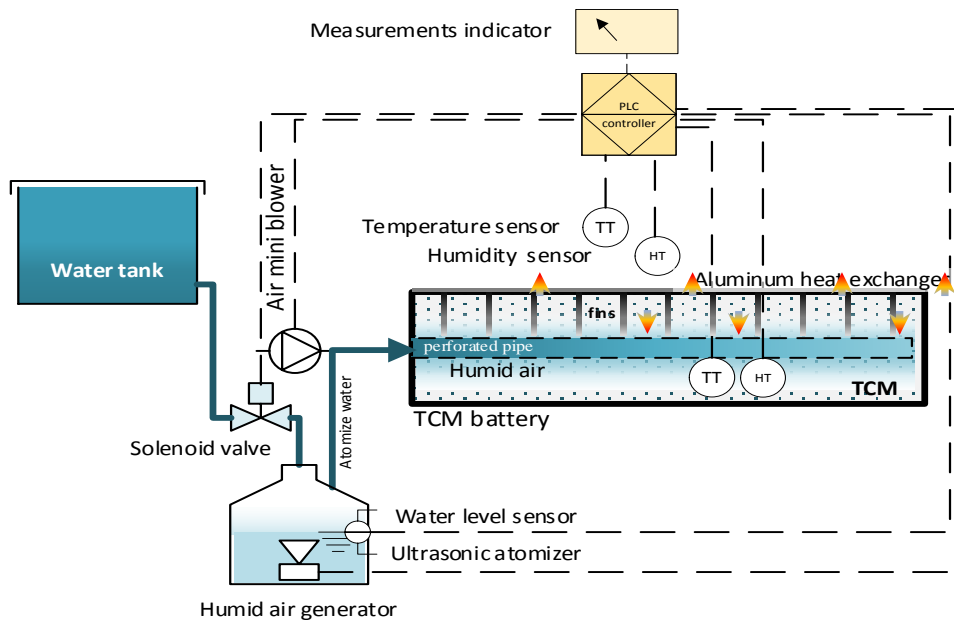


Figure 4. TCM battery energy discharging process flow diagram.

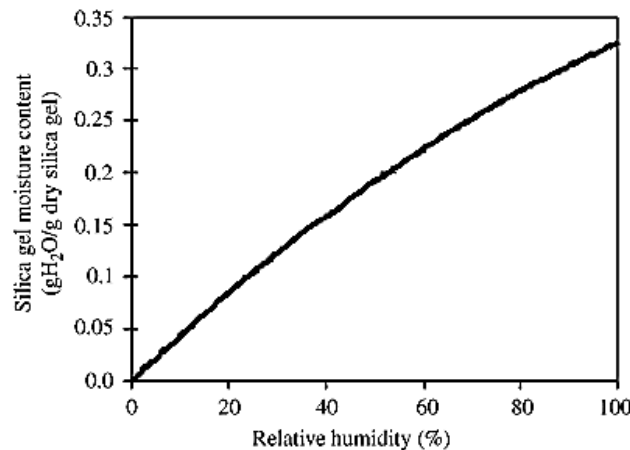


Figure 5. The silica gel moisture equilibrium curve (Chindaruksa et al., 2001).

$$Q_{bat. preheating} = M_{TCM} C_{pTCM} (T_s - T_o) \quad (4)$$

$$Q_{bat. cooling} = M_{TCM} C_{pTCM} (T_o - T_s) \quad (5)$$

where $Q_{bat. preheating}$ is the required TCM preheating energy (kJ), M_{TCM} is TCM mass (kg), C_{pTCM} is the TCM specific heat at constant pressure (kJ/kg°C), T_s is the evaporation temperature (°C), T_o is TCM initial temperature (°C), and $Q_{bat. cooling}$ is the required cooling energy for TCM (kJ).

$$Q_{bat. frame} = k A \frac{\Delta T}{L} \quad (6)$$

where $Q_{bat. frame}$ is the energy absorbed by the battery frame material (W), k is the thermal conductivity of the battery frame (W/m°C), ΔT is the temperature difference between the inner and outer surface of the frame (°C), and L is the thickness of frame (m).

$$Q_{bat. frame} = M_{bat. frame} C_{pbat. frame} \Delta T \quad (7)$$

where $Q_{bat. frame}$ is the heat absorbed by the frame and heating it (kJ), $M_{bat. frame}$ is the mass of the TCM battery (kg), $C_{pTCM frame}$ is the specific heat capacity of the frame (kJ/kg°C), ΔT is the air temperature difference between TCM and TCM (°C).

The charging rate (R_C) of a quantity of desiccant is the amount of water content lost from the desiccant per unit time and can be determined by the mass balance equation for water in the silica gel was calculated from Eqs. (8:10) mentioned by Pramuang and Exell (2007).

$$R_C = -\rho_{TCM} v_{TCM} \frac{dw}{dt} \quad (8)$$

where ρ_{TCM} and v_{TCM} are the bulk density (Kg/m³) and the bulk volume of the dry TCM (m³), dw/dt is the rate of TCM humidification (dry basis), and M_m is the weight of TCM on a dry basis (kg) obtained by weighing a sample periodically over time (the silica gel size 2–5 mm has a bulk density of 670 kg/m³).

The instantaneous energy discharging rate of the self-indicating silica gel battery was calculated from Eq. (9)

$$R_C = G(w_2 - w_1) \quad (9)$$

where G is the flowrate of heated air, w_1 and w_2 are the absolute humidity of the inlet and outlet heated air.

The humidification rate of the TCM battery (energy restoration) was calculated according to Eqs. (10:12).

$$TCM \text{ humidification rate} = \frac{Relative \text{ humidity } (\%) \times M_{air}}{Time} \quad (10)$$

Where M_{air} is the mass of air in TCM (kg), and Time is the required period for increasing the relative humidity (h).

$$M_{air} = (M_{air} + M_{TCM}) - M_{TCM} \quad (11)$$

$$(M_{air} + M_{TCM}) = volume_{TCM \text{ battery}} \times \rho_{TCM} \quad (12)$$

Where ρ_{TCM} is the density of TCM (kg/m³), and M_{air} , M_{TCM} are the mass of TCM-air and TCM, respectively (kg).

The charging energy efficiency (η_{charging}) of TCM (dehumidification process) and discharging energy efficiency ($\eta_{\text{discharging}}$) of TCM (humidification process) were calculated according to Eqs. (13) and (14) respectively.

$$\eta_{\text{charging}} = \frac{\text{TCM net energy}}{\text{Total recieved energy}} = \frac{\text{Total recieved energy} - \text{Energy losses}}{\text{Total recieved energy}}$$

$$\eta_{\text{charging}} = 1 - \frac{\text{Energy losses}}{\text{Total recieved energy}} \tag{13}$$

$$\eta_{\text{discharged}} = \frac{Q_{\text{discharged}}}{Q_{\text{charged}}} \tag{14}$$

where $\eta_{\text{discharged}}$ is the efficiency of thermal energy restoration, $Q_{\text{discharged}}$ is the restored thermal energy from the humidified TCM (W), and Q_{charged} is the stored energy in the TCM battery (W).

3. RESULTS AND DISCUSSIONS

Self-indicating silica gel TCM sample of 143g was dehumidified (energy-charged) directly by solar energy in an open aluminum container (Figure 1, config. I). The dehumidification rate of the sample was $0.37g_w/min$ when TCM temperature was $80^\circ C$. Because the solar energy fluctuates, the sample was rehydrated from ambient air when solar energy decreased. Results showed that it is impractical to charge TCM materials in a such way.

Samples of 50g TCM were dehumidified in an open-ended aluminum tube placed at the center of an evacuated Pyrex-glass tube at the focal axis of a parabolic reflector (Figure 1, config. II). A mini air blower was used to extract the resultant humid air at $1.25 m/s$. Results for energy charging of the self-indicating silica gel, white silica gel, and natural zeolite TCMs at different conditions of solar radiation ($871 - 900 W/m^2$) and treatment time is illustrated in Figures 6; 7; and 8.

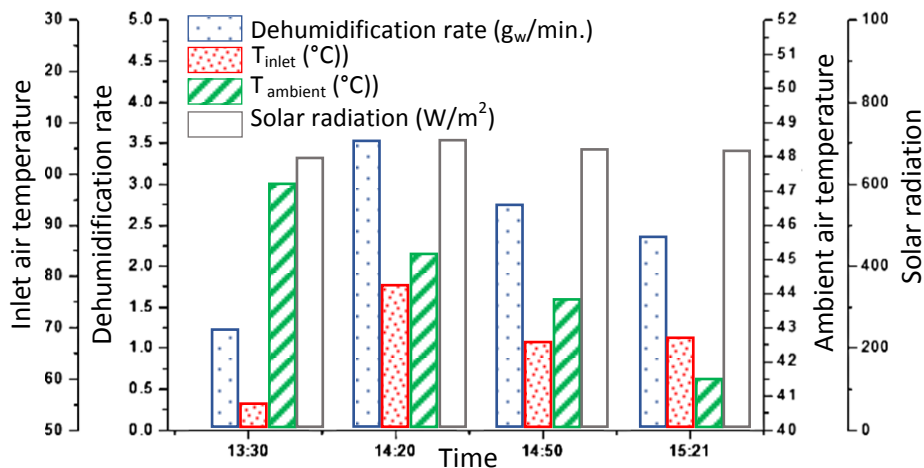


Figure 6. TCM (silica gel self-indicating) dehumidification rate measured during the day.

The results revealed that the TCMs dehumidification rate is directly proportional to solar energy intensity. Overheated TCMs (above $140^\circ C$) affect -irreversibly- their energy storage capacity and useability (Figure 9). To ensure a safe and effective TCMs charging process a set of automatic temperature measurements and control can eliminate the TCM batteries from overheating.

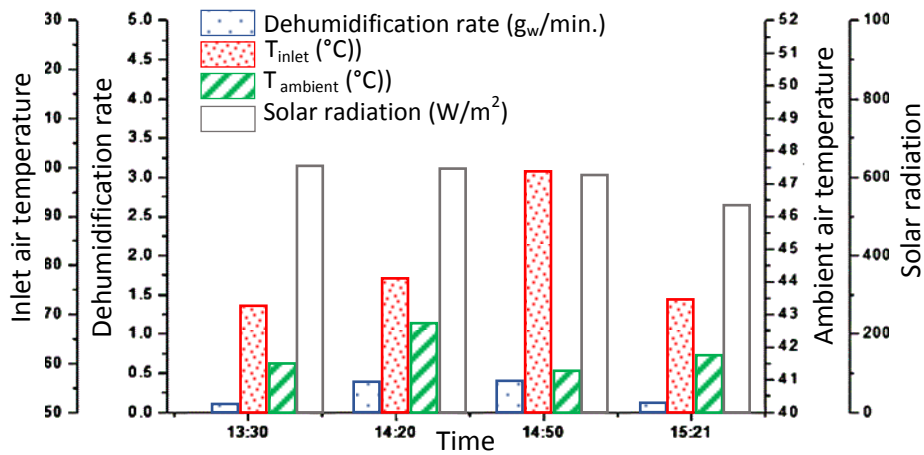


Figure 7. TCM (White Silica gel) dehumidification rate measured during the day.

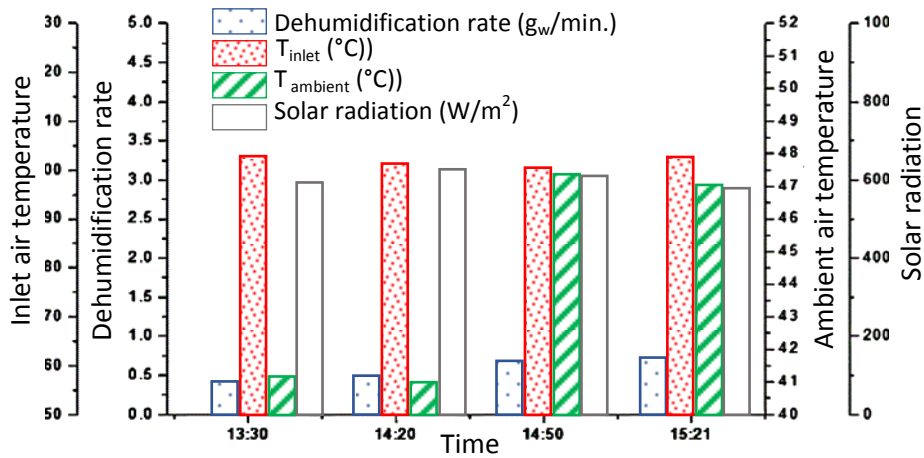


Figure 8. TCM Natural Zeolite dehumidification rate measured during the day.

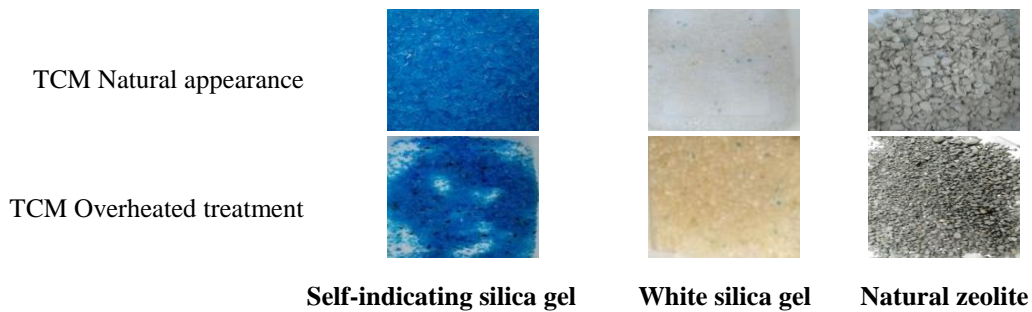


Figure 9. Overheated TCM, color change (burn).

The obtained results from the TCM charging as illustrated in (config. II) are summarized in Table 1.

Table 1 Summary of TCM charging properties in an aluminum tube.

Solar energy TCM		Blue silica gel		White silica gel		Natural Zeolite		
	units	Mn.	Mx.	Mn.	Mx.	Mn.	Mx.	
Solar energy	w/m^2	896	900	860	721	871	900	
Heating temp.	$^{\circ}C$	55.38	86.21	79.81	118.79	124.17	127.59	
Dehumidification rate	g_w/h	1.5	4.5	0.07	0.53	0.6	1.1	Eq. 8 and Eq. 9
Airflow rate	m/s	1.25						

TCMs energy charging by a one square-meter stainless-steel parabolic solar energy collector in a dehumidification, chamber connected to a heat exchanger aluminum tube placed in an evacuated Pyrex-glass tube located at the focal axis of the reflector illustrated in Figure 1.

(config. III). TCM 100g samples were treated with forced hot air from the aluminum heat exchanger pipe at two vertical shelves in a dehumidification chamber (Figure 2). Average temperature and relative humidity for ambient air, heated air, and TCM at top and bottom shelf were measured for self-indicating silica gel, white silica gel, and natural zeolite TCM samples as illustrated in Figures 10; 12; and 13.

The results of the TCM battery charging process are summarized in Table 2. Results for charging the TCM battery in the dehumidification chamber showed that the maximum dehumidification rate of TCM was recorded for materials located at the bottom shelf facing the hot air entrance point compared to results recorded at the top shelf for all treatments (Figures 13; 14; and 15).

Table 2. Summary of TCM charging properties in dehumidification chamber.

Solar energy TCM	units	Blue silica gel				White silica gel				Natural Zeolite			
		Bottom shelf		Top shelf		Bottom shelf		Top shelf		Bottom shelf		Top shelf	
		Mn.	Mx.	Mn.	Mx.	Mn.	Mx.	Mn.	Mx.	Mn.	Mx.	Mn.	Mx.
	w/m ²	921-980				867-730				863-913			
Heating temp.	°C	72.0	92.8	62.6	73.1	74.8	99.5	65.8	93.2	91.3	103.6	85.4	93.2
Dehumidification rate	g _w /h	11.0	16.0	13.0	14.0	13.0	22.0	15.0	19.0	7.0	8.5	6.5	8.0
Air mass flow rate	kg/s	0.0031				0.0027				0.0028			

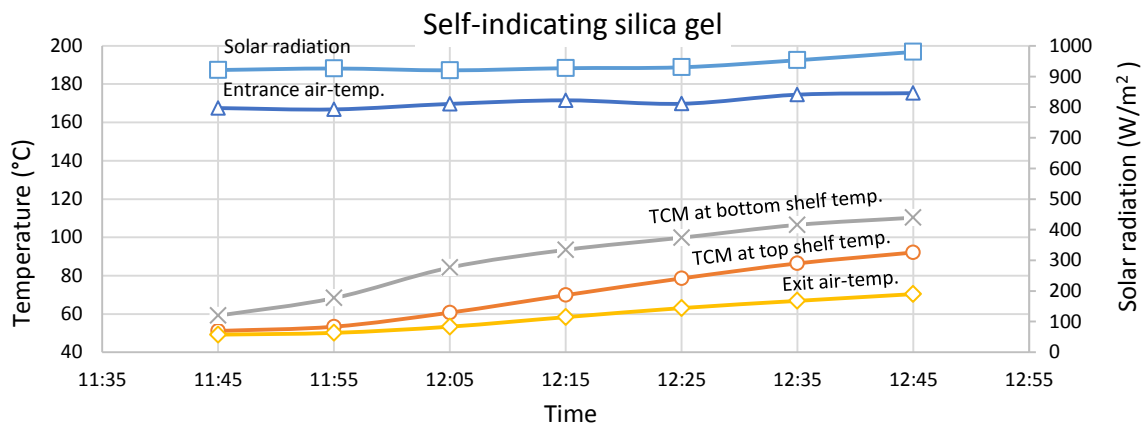


Figure 10. Charging self-indicating silica gel battery process at dehumidification chamber and temperatures distribution at the bottom and top shelves.

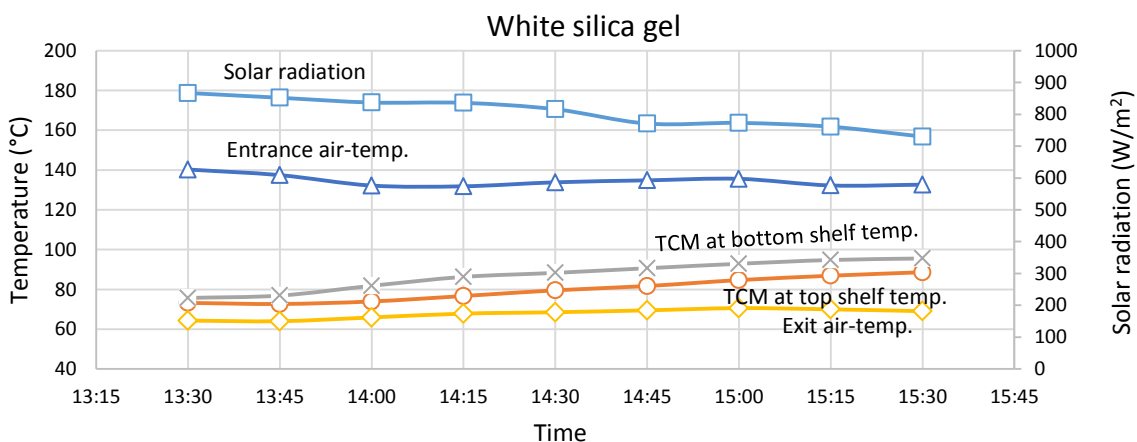


Figure 11. Charging white silica gel battery process at dehumidification chamber and temperatures distribution at the bottom and top shelves.

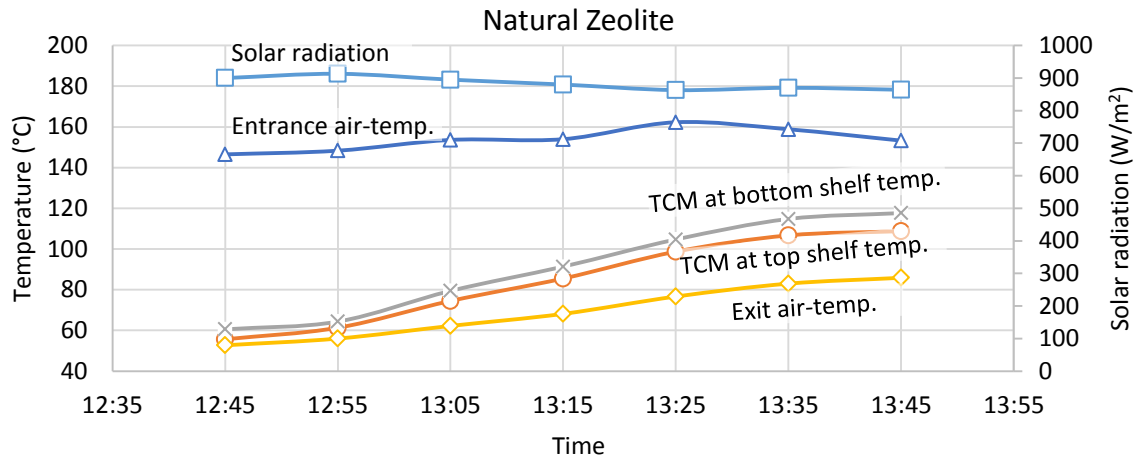


Figure 12. Charging natural zeolite battery process at dehumidification chamber and temperatures distribution at the bottom and top shelves.

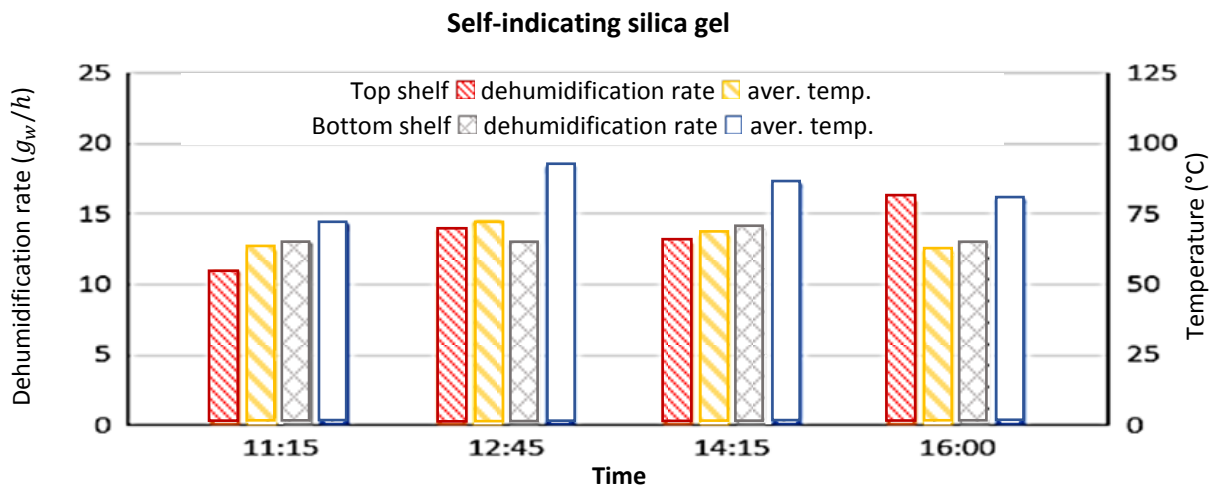


Figure 13. Charging rate of self-indicating silica gel TCM battery (dehumidification rate).

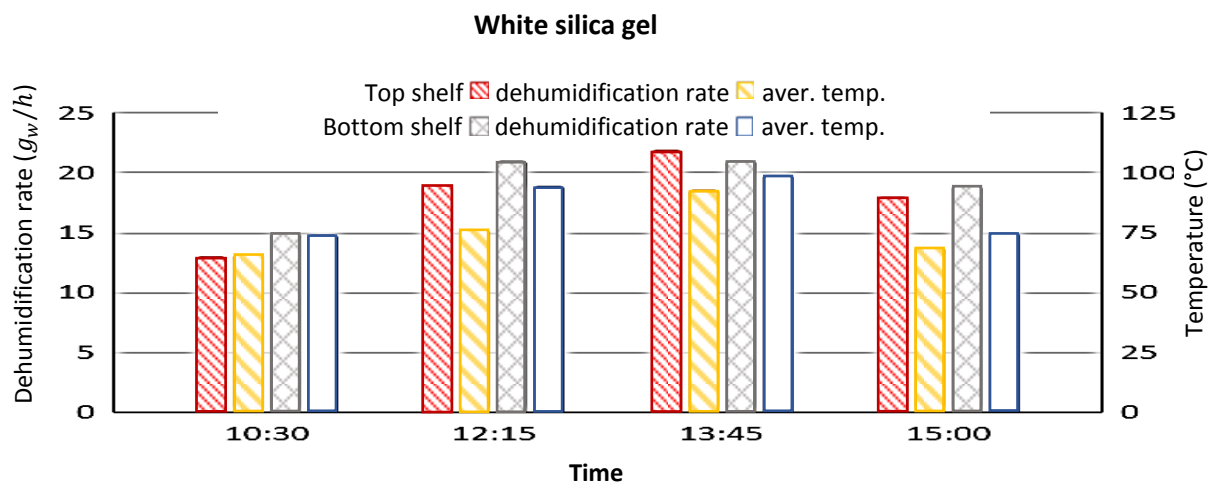


Figure 14. Charging rate of white silica gel TCM battery (dehumidification rate).

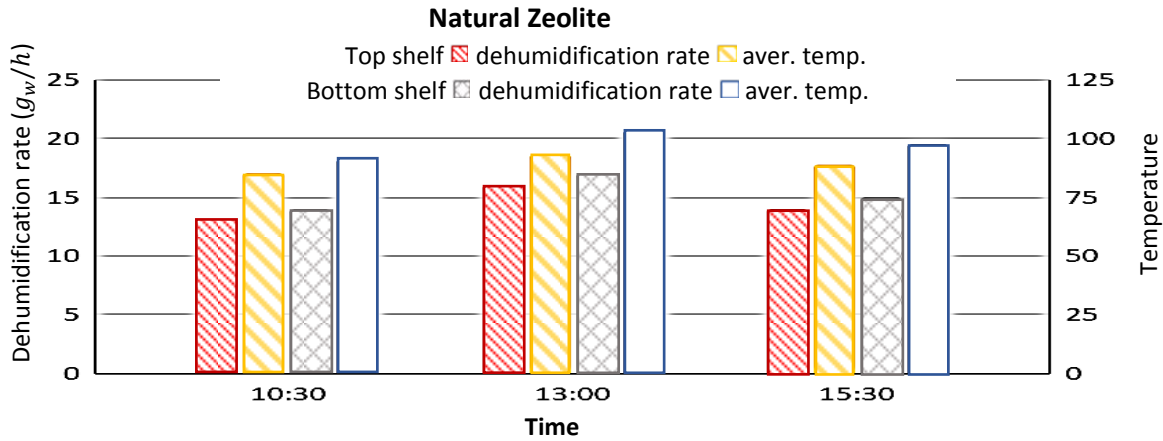


Figure 15. Charging rate of natural zeolite TCM battery (dehumidification rate).

The dehumidification chamber was much suitable for charging TCM because of its suitability in controlling dehydration temperature and rates of hot air, direct removal of humid air, the chamber also can contain a large amount of TCM with simplicity and ability to handle TCM loading and unloading process. For restoring stored energy in the TCM battery, an ultrasonic humidifier unit was used to humid TCMs at a constant rate (Eqs. 8:12). Humidification time and TCM adsorption rate were used to control energy restoration from the battery. Thermal energy restoration from TCMs of self-indicating silica gel, white silica gel, and natural zeolite was illustrated in Figures 16; 17; and 18.

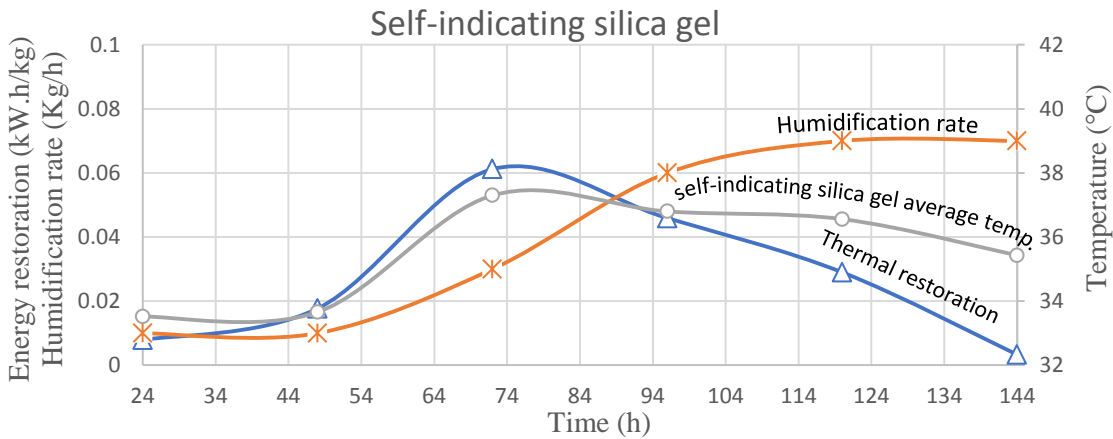


Figure 16. Thermal energy restoration process from TCM self-indicating silica gel battery.

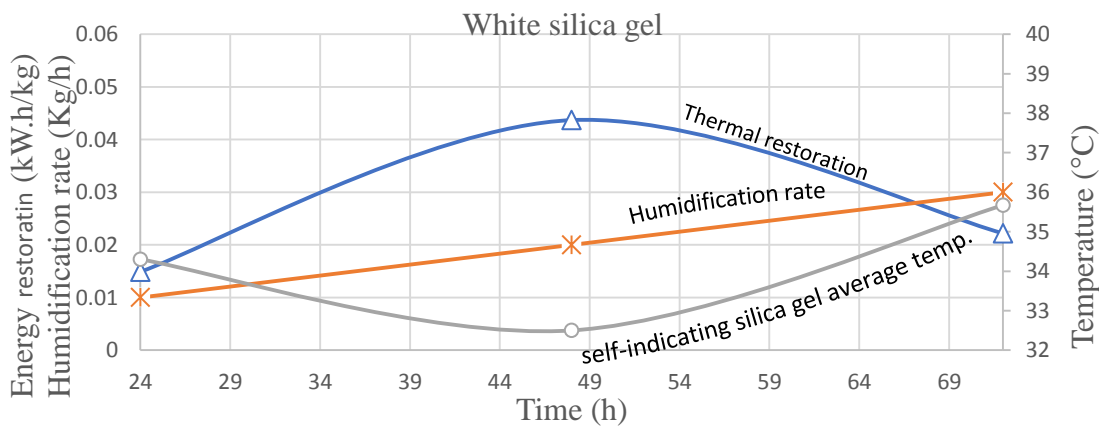


Figure 17. Thermal energy restoration process from TCM white silica gel battery.)

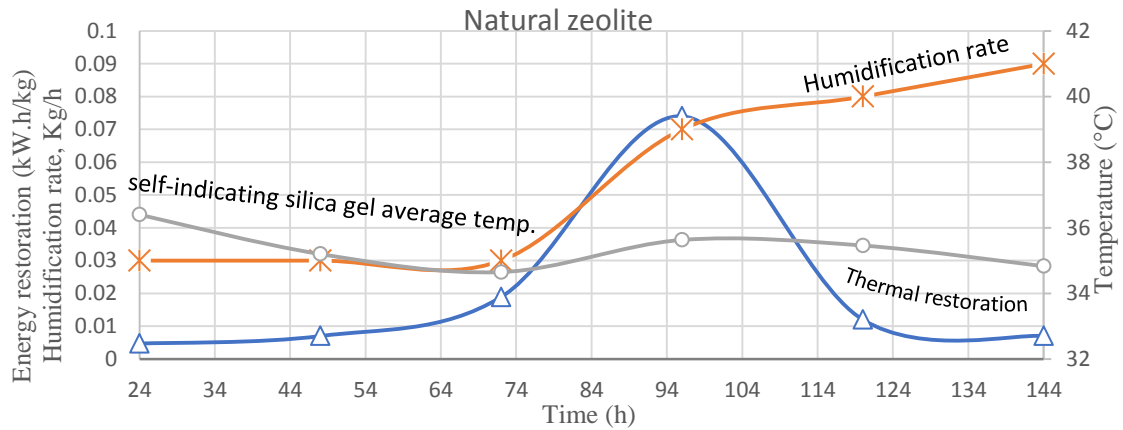


Figure 18. Thermal energy restoration process from TCM Natural Zeolite battery.

Energy restoration of TCM battery is directly proportional to TCM humidification rate. The process is dependent on the TCM time adsorption of humidity. Process time and amount of released stored energy due to humidification rate, are essential results in programming and controlling the ultrasonic humidification unit. Restored energy from the TCM battery of self-indicating silica gel and natural zeolite lasted for six days and produced 0.165, 0.124 kWh/kg, respectively. While the white silica gel battery was depleted after releasing 0.080 kWh/kg in two days (Figure 19).

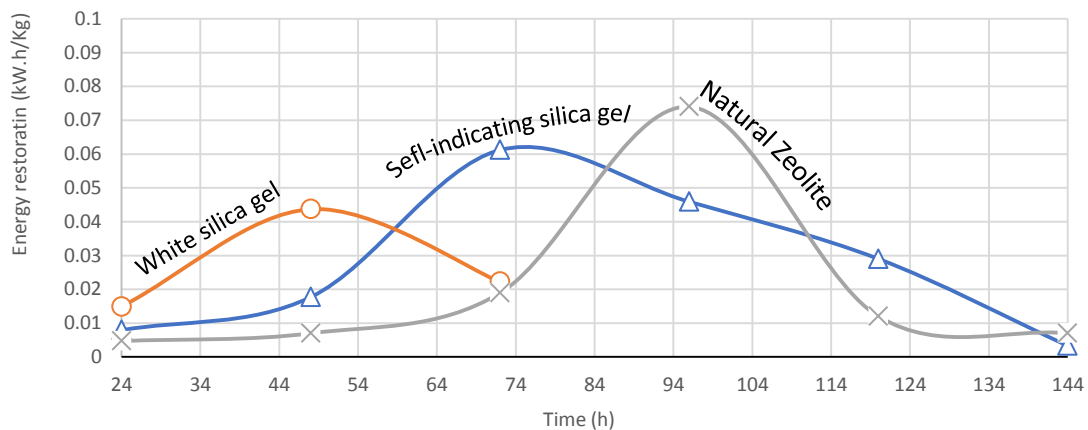


Figure 19. Thermal energy restoration of self-indicating silica gel, white Silica gel, and natural zeolite.

TCM batter charging and discharging capacity and efficiency were summarized in Table 3. Results showed that self-indicating silica gel has more capacity to store energy at low battery size with high energy restoration suitable for low and mid thermal treatment operations.

Table 3. Summary of discharging properties of TCM battery charged by solar energy.

Solar energy TCM		Blue silica gel		White silica gel		Natural Zeolite		Equation
Charged energy	kWh/kg	0.505	0.995	0.28	0.32	0.32	0.78	
Charging eff.	%	56.9	40.1	27.1	29.8	41.3	21.7	Eqs. 2, 7, and 12
discharged energy	kWh/kg	0.0612		0.0437		0.074		
		0.165		0.080		0.124		
discharging eff.	%	32.7	16.6	25	28.6	38.8	15.9	Eqs. 13 and 14

4. CONCLUSIONS AND RECOMMENDATIONS

- The maximum efficiency of the dehumidification (energy charging) process of the TCM self-indicating silica gel, white Silica gel, and natural zeolite was 56.9%, 29.8%, and 41.3%, respectively.
- The maximum efficiency of the humidification (energy restoration) was 32.7%, 28.6%, and 38.8% for Silica gel self-indicating, white Silica gel, and natural zeolite, and respectively.
- It was found that self-indicating silica gel has more energy storage capacity of 0.165 kWh/Kg and a low material volume (size of the TCM battery) compared to white silica gel (0.08 kWh/Kg) and natural zeolite (0.124 kWh/Kg).
- Self-indicating silica gel was more suitable as a battery for applications that requires temperature treatments in the range 33.52 – 37.3°C.
- Direct storage and use of solar energy in a thermochemical form (TCM) can reduce costs and maintenance of renewable energy applications compared to costly photovoltaic systems. TCMs thermal batteries as traditional electrical batteries may function as energy master keys for different agricultural applications, as well as in thermosensitive processing and treatment.
- TCMs technology can be a potential solution to an energy imbalance between energy production and usage as these systems can store a large amount of energy in the long- and short term with minimal heat loss.
- Renewable energy in conjunction with TCMs technology can offer several benefits to accomplish the low-carbon energy goal in low and medium-temperature applications.

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نظام كيموحراري لتخزين الطاقة الشمسية (البطارية الكيموحرارية)

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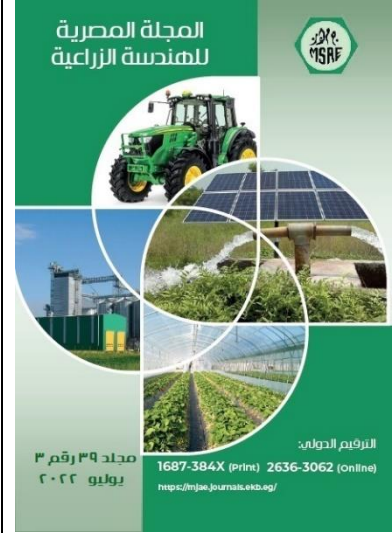
الملخص العربي

تعد الطاقة الشمسية من المصادر غير الملوثة للبيئة والمتوفرة إلا أن استقرار إمداداتها من الطاقة يمثل أكبر التحديات لاستخداماتها الصناعية والزراعية. لذا يهدف هذا العمل إلى استقصاء مدي مناسبة تخزين واستعادة الطاقة الشمسية المباشر بوسائط كيميائية. على أن تكون وحدات تخزين الطاقة متنقلة، قابلة للشحن وتحرير الطاقة الشمسية المخزنة بالمستويات والمعدلات المطلوبة.

أجريت العديد من التجارب لتحديد الوسط الكيميائي الأمثل لتخزين الطاقة الشمسية على كل من مركبات السيليكا جل ذات الدليل اللوني الأزرق، والسيليكا جل البيضاء، بالإضافة إلى الزيوليت الطبيعي. تم شحن المركبات الكيمائية الرطبة بالطاقة بتجفيفها عبر مركز شمسي على شكل قطع مكافئ بمساحة متر مربع. اختبرت بطارية كيموحرارية بسعة ٣,٥ كجم من المركبات الكيمائية المخزنة للطاقة داخل حاوية من الألومنيوم لتعمل كمبادل حراري متنقل لشحن وتفريغ الطاقة الحرارية. وأمكن التحكم في معدلات ومستويات الطاقة الحرارية المحررة من البطارية من خلال القياس والتحكم المبرمج بمعدلات مزيج الهواء والرطوبة فيه.

أظهرت النتائج أن السيليكا جل ذات الدليل اللوني الأزرق هي المادة الأصلح لتخزين الطاقة الحرارية من بين المواد المختبرة لسعتها الحرارية التي بلغت ١٦٥ واط/كجم في الساعة مقارنة بكل من الزيوليت الطبيعي والسيليكا جل البيضاء بسعات تخزين ١٢٤ و ٨٠ واط/كجم في الساعة بالترتيب. وبلغت كفاءة استرداد الطاقة الحرارية من البطارية الكيموحرارية لمادة السيليكا جل ذات الدليل اللوني الأزرق ٥٧,٧٪، في حين أن كفاءة الزيوليت الطبيعية والسيليكا جل البيضاء بلغت ٤٥,٨٪ و ٣٩٪ على الترتيب.

خُصص العمل إلى أن التخزين والاسترداد للطاقة الشمسية الحرارية ضمن وسائط كيميائية تميز بالفاعلية وبالبساطة في التشغيل والصيانة. ويمكن أن تُسهم البطاريات الكيموحرارية المتنقلة في تيسير استخدام الطاقة الشمسية للعمل ضمن مختلف التطبيقات بالمزرعة.



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الكلمات المفتاحية:

الطاقة الشمسية؛ تخزين الطاقة؛ البطاريات الحرارية.