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Comparative Critique of Thermal Energy Storage Technique in Solar Chimney Power Plants

Ali A. Ismaeel*[1], Hussain H. Al-Kayeim*, Aklilu T. Baheta* and Mohammed A. Aurybi*

Abstract – Similar to any solar thermal conversion system, the solar chimney is suffering from the non- availability of solar energy at night and during cloudy conditions. One technique to overcome this setback is the integration of the solar chimney with thermal energy storage, which brings about extended functionality and enhanced performance of the system. This paper presents an overview of the thermal energy storage techniques suggested/reported so far for the solar chimney power plants. Many types of sensible and latent materials with descriptions have been discussed in this paper. The review presents a summary overview of the physical process, experimental and theoretical studies carried out on integrated solar chimneys with thermal energy storages. In addition, the paper presents proposed hybrid thermal materials as thermal energy storage technique for solar chimney power plants. The proposed hybrid type of material is simple and capable to absorb and store the solar energy in the solar collector of the plant leading to higher performance as well as extend the operational time to produce power.

Keywords – Phase change material, solar thermal energy, solar chimney, TES, thermal storage materials.

1. INTRODUCTION

One of the solar thermal energy applications is the solar chimney power plant (SCPP) which is aimed to produce electricity through series of energy conversion within simple apparatus [1]. SCPP as a low temperature solar thermal power plant uses the environment air as its working fluid. This power plant consists of three main parts: a solar collector, solar chimney and turbine generator [2]. Air is heated as a result of the greenhouse effect under a collector roof. The warm air underneath the collector moves towards and up into the center of chimney as a result of buoyancy and temperature difference between the ambient air and the warm air inside the plant. A turbine is set in the path of air to convert the kinetic energy of the flowing air into mechanical rotating shaft to produce electricity [3], [4]. Schematic diagram of SCPP is shown in Figure 1.

In 1981, SCPP was proposed, designed and built in Manzanares (about 150 km south of Madrid in Spain) by the German structural engineering company, which funded by German Ministry of Research and Technology. The chimney height was 195 m with 10 m diameter and the collector had a radius of 122 m. The plant designed to produce 50 kW electricity [5], see Figure 2 [1].

Considering the result of the experiment in the Manzanares project and other research models that have been developed so far, the efficiency of SCPP is still below (2%) and the output power depends mainly on the chimney height and the surface area of the collector or depends on other ways to enhance their efficiency [7]. Increasing the chimney height or extending the area of solar collector means very high installation cost of SCPP; and therefore, requires high financial investment.

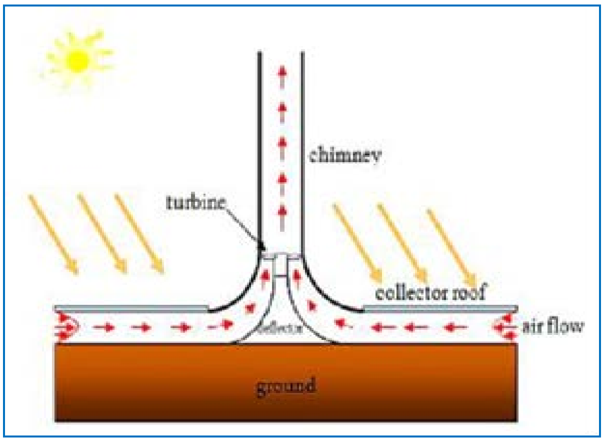

Fig. 1. Schematic diagram of solar chimney [1].

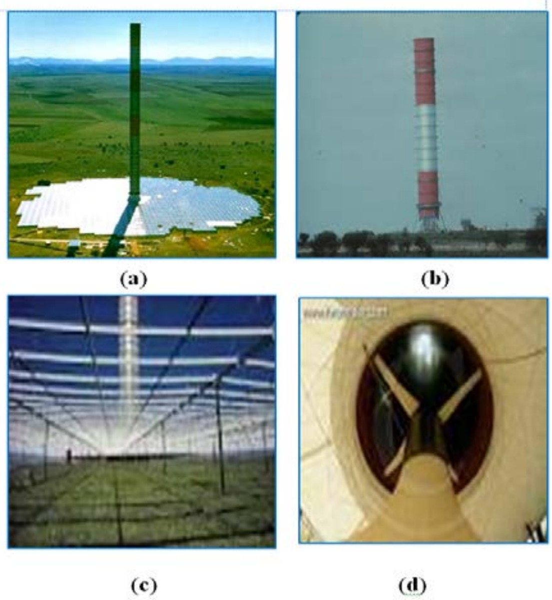

Fig. 2. (a) Solar chimney power plant in Manzanares, Spain; (b) chimney tower; (c) collector; (d) wind turbine; [6].

The aim of this paper is to present a review of the thermal storage techniques used to enhance the solar collectors which have been carried out by previous

*Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia.

[1]Corresponding author; Tel: +60103678374.
E-mail: ali_abdul_wahab@yahoo.com

researchers to rise the collector. In addition, comparisons between the reported techniques have been presented and discussed. Furthermore, the authors suggested a new method of hybrid storage method, which it is believed to enhance the instantaneous system efficiency, and extend the operational period after the sunset.

2. THERMAL ENERGY STORAGE METHODS IN SCPPs

In thermal energy storage, energy can be stored as a change in internal energy of a material in the form of sensible heat, latent heat and thermo-chemical heat or combination of these [8] as shown in Figure 3. Storage of thermal energy in the form of sensible and latent heats has become an important aspect of energy management with the emphasis on efficient use and conservation in the SCPP.

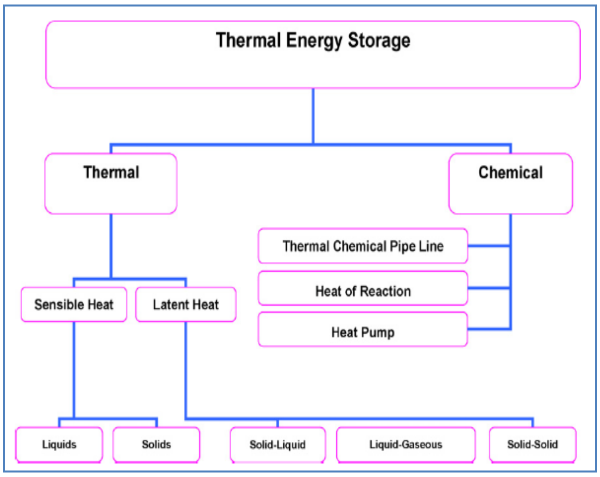

Fig. 3. Different types of thermal storage of solar energy application [37].

2.1 Sensible Heat Storage

In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid, which does not change its phase during this process. A variety of substances have been used in such system .These include solid like rocks, pebbles and liquids like water, oils. The SHS depends on the temperature change, the specific heat of the material and the amount of storage material [9]. The following literature survey focuses on the thermal storage techniques by different sensible materials in the solar collector on the SCPP. The review covers the experimental, numerical and mathematical studies.

2.1.1 Solid –thermal energy storage

Many studies have examined and enhanced the efficiency of solar collector by using different solid materials. In line with this the experimental and theoretical study introduced by Shyia [10] investigated the effect of ground type on the collector efficiency and the canopy height above the ground.in the study, the following ground materials were considered (aggregates, asphalted, sand, soil, and underneath asphalted soil). The results showed that asphalted was a good absorbing medium, while the lowest height provided the best performance. Abdulceli [11] conducted an experimental investigation in Turkey (Adiyaman University campus area); to design a special layered soil. The chimney was made of 0.07 m thick sheet. It has a 15 m height and a 0.8 m diameter. It receives the sunlight at all hours of the day in open area. A 0.05 m thick aluminum foil, covered with glass wool, was placed in the center of the collector. The collector height was adjustable to (0.05-0.35 m) with (6°) slope. The ground floor was 27 m diameter and 0.5 m deep pit. It was constructed as follows: the pit was covered by aluminum foil, 0.05 m thick glass wool, 0.1 m thick gravel, 0.05 m sand, 0.05 m glass and 0.25 m asphalt pave (top surface) compressed onto the glass wool as shown in Figures 4, 5 and 6. The authors investigated the temperature and air velocity distribution along the day. The results showed that the temperature and velocity were influenced by the heat stored in the ground [11].

Fig. 4. Photograph of the Abduulceli prototype [11].

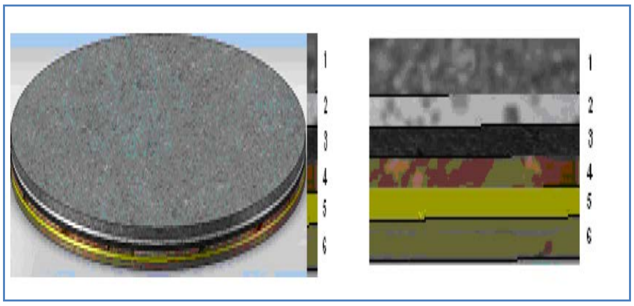

Fig. 5. Description of the special ground layer (1. Asphalt, 2.Glass, 3. Thick sand 4. Gravel 5. Aluminum foil with glass wool 6. Ground floor). [11].

Fig. 6. Pictures showing the construction steps of ground of the Abdulceli prototype (A ground floor, B Aluminum folio with glass wool, C Gravel laying, D Sand, E Glass laying, F Asphalt paved) [11].

As shown in Figure 7, a model of SCPP in the region of Baghdad-Iraq was conducted by Chaichan to study the influence of the basement types on the chimney air temperatures. Three basements such as concrete, black concrete and pebbles were studied. The results showed that the best solar chimney efficiency was 49.7% from the pebble base as shown in Figure 8 [12].

Fig. 7. Photograph of the Chaichan prototype [12].

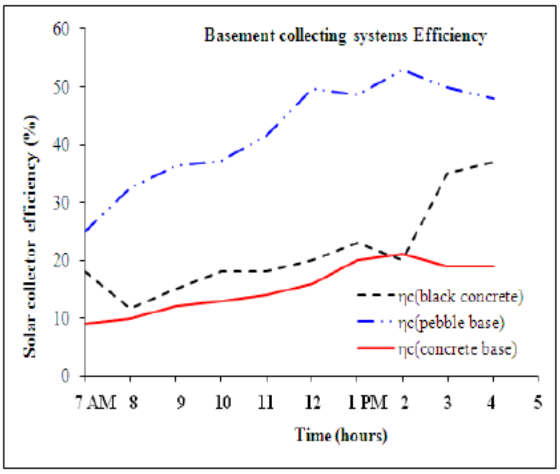

Fig. 8. Average efficiency differences for day hour for basement system [12].

The effect of various types of soil in SCPP power output was established by Pretorius *et al.* [13]. The authors compared the power outputs of five different ground types: sandstone, granite, limestone, sand, and wet soil. They found that the SCPPs employing the wet soil and the sand have the lowest and highest power outputs, respectively, and different materials lead to varying power outputs during the daytime and at night. Their also concluded that increased ground absorptivity holds positive effects on annual solar chimney power output. Zheng *et al*. [14] performed unsteadily numerical simulations to analyze the performance of the solar chimney power plant systems with energy storage layer by using the commercial software FLUENT 6.3. Numerical models were developed to describe the flow and heat transfer mechanisms of the collector, chimney and the energy storage layer. The responses of different energy storage materials to the solar radiation, and the effects of these materials on the power with different solar radiation were considered. The numerical simulation results showed both the soil and gravel have suitable values of the property of thermal inertia, and they could be used as energy storage materials. Also, the large part of energy from the solar radiation on sunny days can be stored in the energy storage layer and released at night or on cloudy days. Tingzhen *et al*. [15] performed numerical simulations to analyze the characteristics of heat transfer and air flow in the SCPP with soil and gravel as a thermal storage layer. The simulation result showed the heat storage ratio of the energy storage layer which was higher than 80% decreased at first and then increased when the solar radiation increased from 200 W/m² to 800 W/m². The influences of the soil thermal inertia and the soil compaction degree on the output power generation have been studied by Hurtado *et al*. [16]. The authors analyze the thermodynamic behavior and the power output of a SCPP over a daily operation cycle taking into account the soil as a heat storage system , through a transient numerical simulations under non – steady conditions and the numerical result have been validated with the Manzanares project. The result showed the higher compaction degree of soil causes an increase on total energy generation of 10% as a shown in Figure 9 [16].

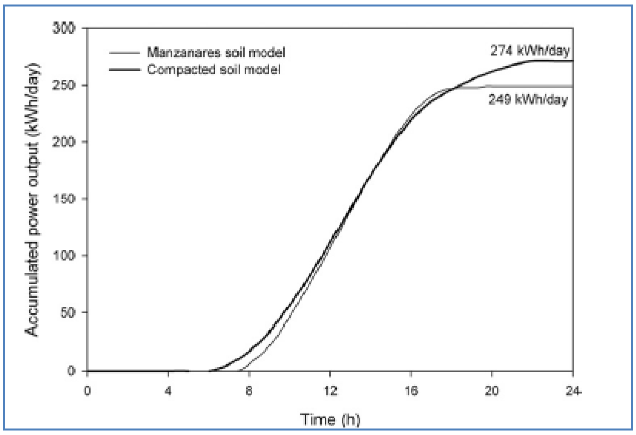

Fig. 9. Numerical investigation on the soil compaction influence. Accumulated power output [16].

Ketlogetswe *et al*. [17] designed and built a pilot SCPP for research at the request of the Ministry of Science and Technology in Botswana. The absorber materials under the roof were made up of two layers of compacted soil about 10 mm thick and a layer of crushed stones. The crushed stones' layer was spread on the top surface of the compacted soil layer as shown in Figure 10.

The solar collector was manufactured from glass reinforced polyester material, and has an inner diameter of 2 m and a height of 22 m. The collector roof was made of a 5 mm thick clear glass supported by a steel framework. The collection area reached at approximately 160 m^2. This experiment was done from 7 October to 22 November 2005. Figure 11 described the operating data of the solar density, temperature difference and velocity under different conditions.

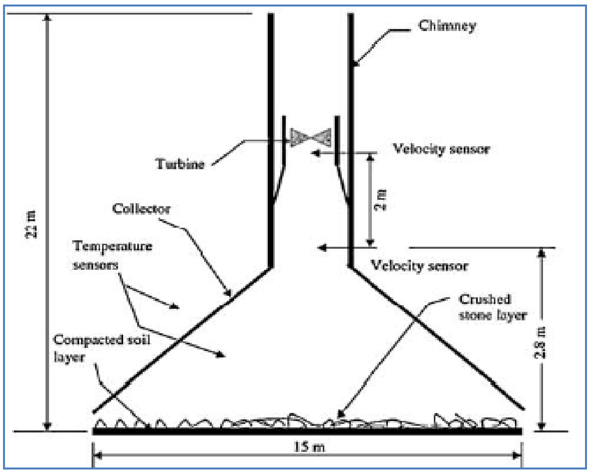

Fig. 10. Schematic overview of the Botswana solar chimney power plant [17].

The experiment result showed is for the time period between approximately 6:00 and 8:00 h, with an increase in solar density from approximately 100 to 500 W/m2, airflow velocity gradually increased to a high value and then remains nearly constant until approximately 14:00 h, despite the increase of the solar radiation to a maximum peak of 950 W/m2 approximately at 12:00 h. Approximately 47% of incoming solar energy is absorbed and stored by the ground and later released when the local temperature decreases. The temperature difference ranged from about 2-8 0C at 6:00 a.m. to 7.5-8 0C at noon, and air velocity ranged from 1 to 2.5 m/s with the diffuser installed and from 2 to 4 m/s with the diffuser removed [17].

Mohsen *et al*. [18] used the asphalt at the base of solar collector to enhance the thermal energy storage activity. The work was presented as and analyzed as thermal simulation model of a collector canopy with double glass and the maximum height of the canopy was 1.3 m. The result showed the Nusselt number for low canopy height determine by Equation 1 and high canopy by Equation 2:

$$Nu = \frac{0.0037\ Re^{0.8}\ Pr}{1 + 2.44\ Re^{-0.1}(Pr^{2/3} - 1)} \qquad (1)$$

$$Nu = 0.14Ra^{1/3} \qquad (2)$$

Based on the asphalt concrete can absorb a considerable amount of the solar radiation [18], [19], [20]. A novel study used the pavements to produce the energy suggested by Alvaro Garcia *et al.* [21]. The parallel air conduits integrated in the pavements structure and connected with a PVC updraft tower.

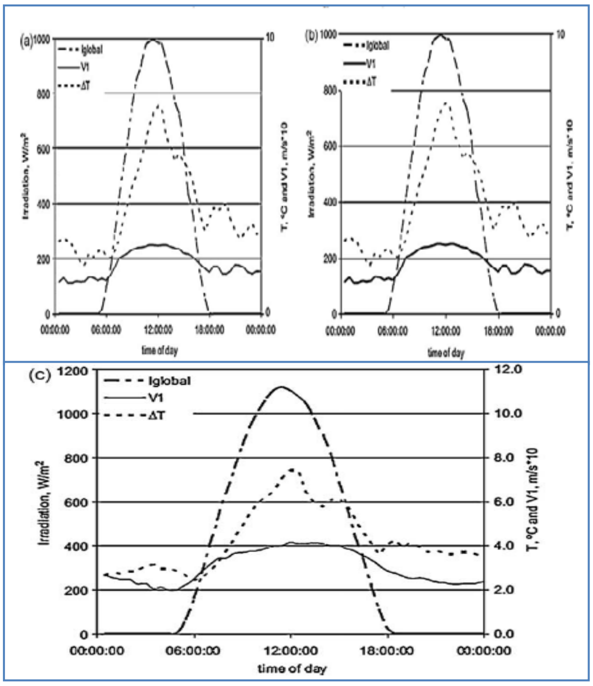

Fig. 11. An average of measured solar radiation, temperature and velocity. (a) For selected 5 clear days of October (with turbine installed), (b) for selected 6 clear days between 19 and 30 October (with turbine removed), (c) for 6 days between 14 and 21 November (with turbine and diffuser removed) [17].

The temperature difference between the ambient air and asphalt concrete can be used to create an air flow. Solar turbine could be used to produce the power and to decrease the temperature of pavement in summer or to increase it in winter, see Figure 12. Both the updraft tower height and the influence of the air flow on the total temperature of the pavement were analyzed.

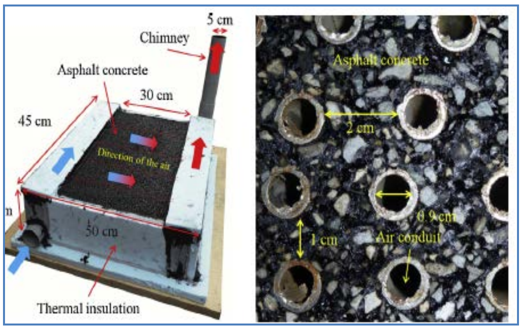

Fig. 12. Detail of the air conduits in the asphalt [21].

The results obtained from the solid thermal energy storage investigations can be summarized into two parts. The first part compared between many kinds of absorbing materials on the ground of each model to select the best material that give higher solar collector performance as shown in Table 1. The second part used one absorbing materials on the ground for their models and study the effect on the SCPP performance in the variable operating conditions as a shown in Table 2.

Table 1. Comparison between different heat storage materials in SCPP as reported in the literature.

Authors	Analysis of Methodology	Different heat storage materials utilized.	Best material
Shyia, 2002	Experimental and theoretical	Aggregates , asphalt ,sand, soil	Asphalt
Chaichan, 2011	Experimental study	Concert , black concert , black pebbles	Black pebbles
Pretorius, 2006	Analytic study	Wet soil, sand, sandstone, limestone, granite	Sand

Table 2. One type of solid thermal storage materials proposed by some previous studies.

Authors	Analysis of Methodology	Proposed Solid Thermal Storage Material
Tingzhen *et al*., 2009	Numerical study	Soil and gravel
Zheng *et al*., 2010		
Mohsen *et al* , 2012	Numerical study	Asphalt
Alvaro Garcia *et al*., 2014	Experimental study	Asphalt
Ketlogetswe *et al*., 2008	Experimental study	Soil and crash stone

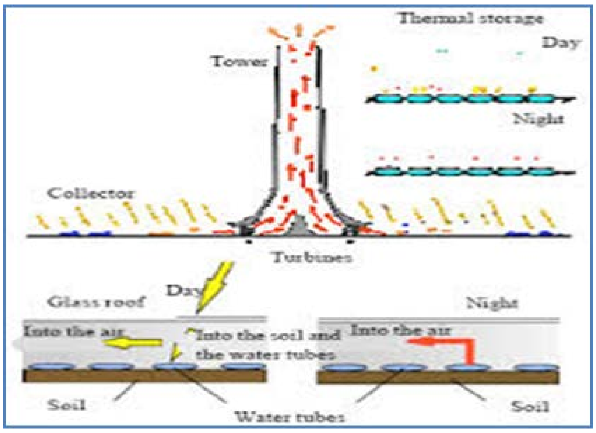

Fig. 13. Heat storage underneath of the roof collector using water-filled black tubes [24].

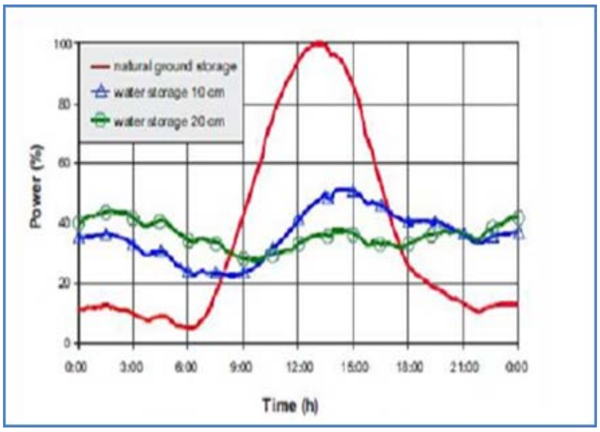

Fig. 14. The effect of water tubes – thermal storage on power output with respect to time [25].

Fig. 15. Photograph of the Bundoora prototype [26].

2.1.2 Liquid-Thermal Energy Storage

Water filled black tubes were laid down side by side on the radiation adsorbing soil under the collector .The sealed tubes were filled with water, so that no evaporation can take place, as shown in Figures 13, 14. At night, when the air in the collector started to cool down, the water inside the tubes released the heat which was stored during the day. Heat storage with water worked more efficiently than with soil alone. This occurred due to the low water velocities from natural convection in the tubes. Also, the heat transfer between water tubes and water was much higher than that of the ground surface and soil layers underneath [22], owing to the heat capacity of water which is above five times higher than the soil. In 2009, the mathematical model for the solar chimney power plant with water as a thermal storage was developed by Hammadi [23]. The effects of thermal storage system for power production of the plant and the thickness of the water storage layer were analyzed. A numerical simulation using the finite difference method was presented by Beranrdes *et al.* [24]. This study aimed to analyze the sensible heat storage physical process in a solar updraft tower integrated with water bags. The numerical results showed the insulated water bags increased the solar collector efficiency and allowed to generate the power in the night.

In 2002, a small – scale solar chimney combining a solar pond with an updraft tower was constructed at the RMIT campus in Bundoora (20 km north of Melbourne, Australia). The use of solar pond as a substitute for a solar collector as a thermal heat storage was presented in this study. The updraft tower was flexible circular ducting and supported by structure of a small particular wind generator, see Figure 15 in [26].

Fiorenza *et al*. [27] studied the ability of using the salt gradient solar pond for power generation. Later, Akbarzadeh *et al*. [28] had examined the concept of integration a solar pond with a chimney to produce the power in salt an affected areas. The study proposed two towers to produce electricity as shown in Figure 16. In the first one a non –direct contact heat exchanger while the second one used a direct contact heat exchanger. Heat was removed from the solar pond by extracting hot brine under the interface and pumping the gradient layer, the bottom convective zone and pumping it through the tower. After delivering its heat the water was returned to the bottom of the solar pond .Therefore the ambient air in the tower was heated and it started to move towards the turbo generator to produce the electricity [28]. The thermal model of this study when compared with Manzanares project results showed that the solar pond had 10% greater electricity than the solar collector and could produce 60 kW power.

Xinping *et al*. [29] proposed to build solar chimney integration with salt lakes working as heat storage in Qinghat-Tibet plateau, China. Mathematical model was investigated in this study. It was found that SCPP if built in the plateau can produce twice as much power as an SCPP if built on the same latitude of other regions in China.

Joining together solar chimney system, solar energy storage and evaporation, condensation and desalination process of seawater were introduced by Zuo *et al*. [30]. In this integrated system as shown in Figure 17, the water body is the solar energy absorber, the whole heat –source when the system works over night or on cloudy days. The seawater depth affected on the fresh water production capacity and solar energy storage under actual weather conditions was analyzed in this study. Three small-scale contrasts experimental devices of solar chimney-sea desalination integrated system are set up by the authors as shown in Figure 18. The device is mainly composed of six parts: (1) chimney with 5 mm thickness, gray PVC pipe with 80 mm inner diameter and 2500 mm height; (2) heat collector plate, 3.5 mm thickness and transparent PC flat plate; (3) tank cover, 3.5 mm thick and transparent glass plate; (4) sink, 8mm thick PVC flat -plate; (5) wall: 3.5 mm thick of double glass; (6) 25mm insulation materials covering the side and bottom of the experimental device [30]. The results show that too deep depth of water layer will enhance the thermal inertia of the water and reduce the mass flow rate of fresh water production (Table 3), that means, the shallow water layer is better than the deep one for evaporation. Also the researcher mentioned that there was optimal water depth and that depth increases the fluctuation of the hot air temperatures and makes sure that its positive, but this best depth is not calculated in this work and the authors told its need further studies.

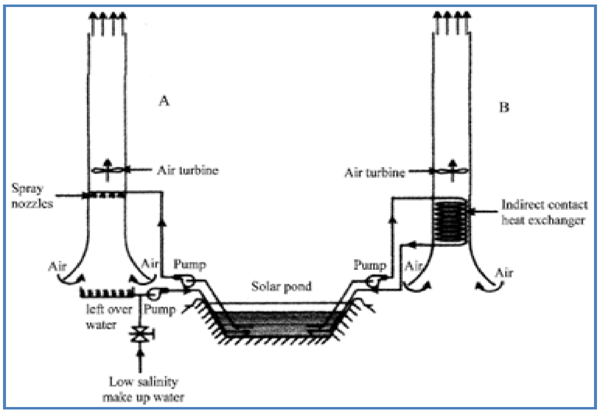

Fig. 16. Concepts for combining a chimney with a solar pond to generate power [28].

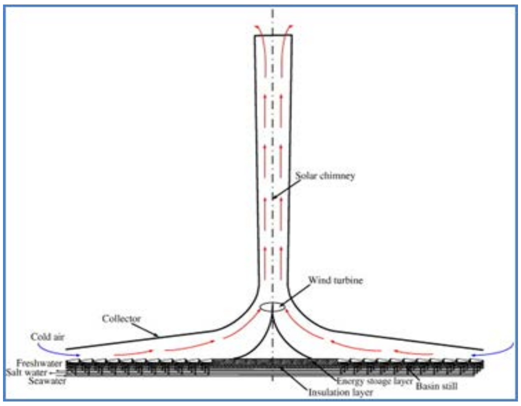

Fig. 17. Structure diagram of solar chimney – sea desalination integrated system [30].

Fig. 18. Integrated experimental devices [30].

Table 3. Summary on total volume water experimental days [30].

Experimental days	2008-8-23/24/25			2008-8-26/27/29	
Seawater depth (m)	Hw =0.12m	Hw =0.10m	Hw =0.08m	Hw =0.08m	Hw =0.04m
Total volume of fresh water (g/m^2)	2780	2980	3181	3950	5046

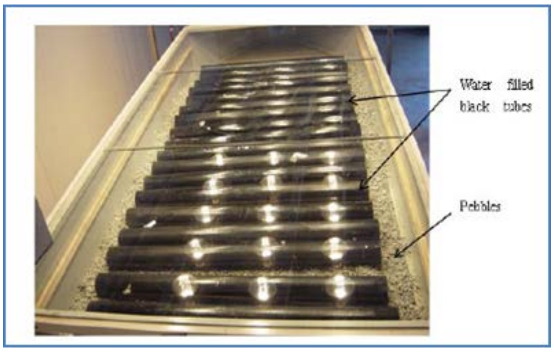

Fig. 19. The solar collector layout [31].

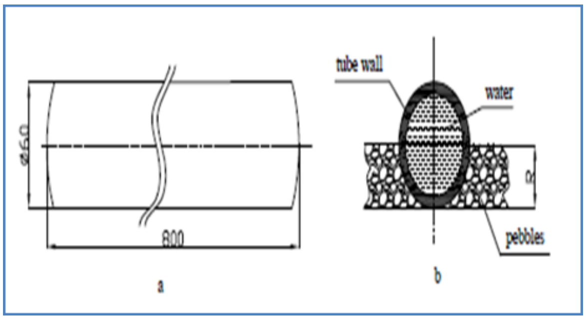

Fig. 20. Profile chart of thermal storage in the solar collector [31], (a) The dimension of water tube for thermal storage material, (b) Cross- section of water in radial.

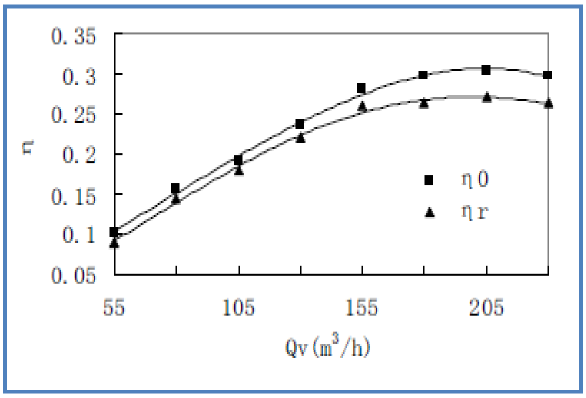

Fig. 21. The influence of the packing height on temperature difference [31].

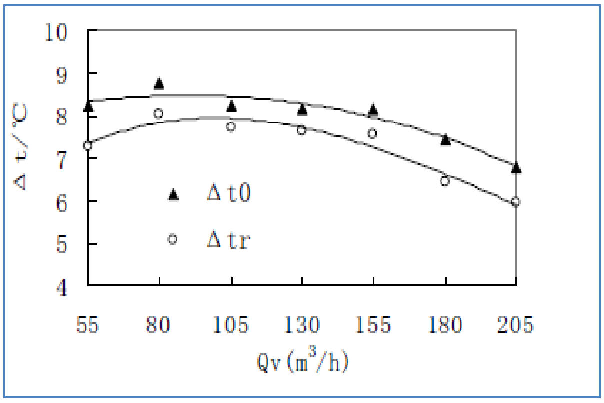

Fig. 22.The influence of the packing height on solar efficiency [31].

2.1.3 Hybrid solid- liquid thermal energy storage

Huang *et al*. [31] studied and described details of the experimental process on the hybrid thermal storage material in the solar collector. In this study two experimental modifications were tried on the thermal storage material in collector pebbles along with water tubes having a black surface combining pebbles and water tubes, see Figures 19 and 20. The result showed that the temperature difference between the inlet and outlet of the collector which changed gradually but collector efficiency was increased at first instance then reduced slightly as the volume flow rate increase using both the liquid and solid thermal storage materials to enhance the solar collector performance as shown in Figures 21 and 22. Also the effect of packing height of the pebbles on the efficiency and temperature increasing for the collector was conducted and the results showed the zero level of the pebbles gave more efficiency and temperature increasing for the system than the radius level with same volume flow rate.

Fanlong *et al*. [32] prescribed a mathematical model of fluid flow, heat transfer and power output features of solar chimney power plant generating systems and analyzed the influence of the material and depth of energy storage medium upon power output. The simulation results demonstrated that the hybrid energy storage system with water and soil can effectively decrease the power output fluctuation. Also, the power output of solar chimney showed to become quite stable when the water depth reached 0.1m, whereas the increase in depth would not influence this stability.

2.1.4 Thermal absorber plates

In 1997, a SCPP was built by Pasurmarth and sheriff in Florida, USA [33]. Their presentation was attached with the aluminum absorber plate on the ground under the collector roof. The testing focused on trying and enhancing the heat transfer of the collector performance. The diameter of collector is 9.15 m and the chimney height 7.92 m. Its diameter gradually decreased from 2.44 m to 0.61 m base to the summit. Two enhancements were tried on the collector. Firstly the collector base type.1 was extended from 9.15 m to 18.3 m (type 2) and the second enhance used the canvas absorber between the roof and the aluminum plate absorber inside the type.2 and type. 3. Results showed in the type. 3, both of absorber plat and the canvas absorber improved the conversion efficiency of collector and hence power output [33]. A solar chimney might be incorporated into the roof of building and houses. A glazed collector installed on the slopping roof heats air before it rose into the chimney. The advantage of this system is that the solar heats gains and the slope of the roof can be designed to capture maximum solar radiation [34]. A wind rotor with generator is to be installed in the Roof top solar chimney to produce the electric power [34]. A schematic diagram of the roof top solar chimney has been shown in Figure 23. Enhancing heat resource by using absorber plate integrated under transparency roof proposed by Serrjaya and Al-Kayeim [35]. This system was studied under various operational conditions and different geometries. Results showed that there were two requirement points to develop the Roof top solar chimney for small-scale power generation. First to enhance the solar energy by better absorber plate, secondly it is the use of thermal back up to allow continuously to generate the power during night and cloudy days and the Serrjaya and Al-Kayeim prototype explain in Figure 24 [35].

Experimental model of SCPP was designed and constructed in Iraq and studied at Iraqi weather conditions by Haider [36]. The SCPP consists mainly of a solar collector part (transparency roof, absorbing plate and water storage tank) and the chimney made from transparent property as shown in Figure 25 which represents the model. The results showed the chimney wall with transparent property would increase available power by 44.7%. Furthermore, the energy gained by black absorber plate upper water tank surface was higher than the one that was gained with transparent surface by 58.75% and the use of water tank as a thermal storage would enable the SCPP to work during the night hours.

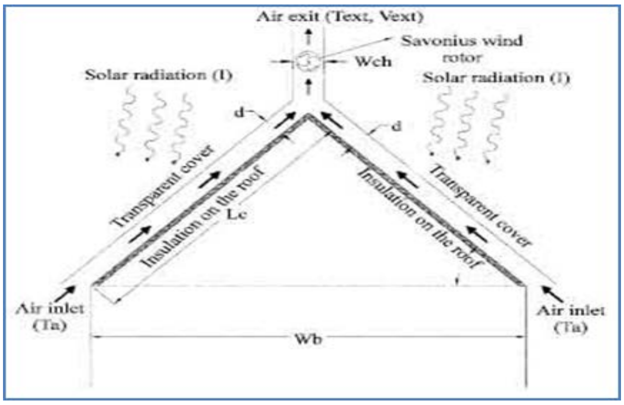

Fig. 23. Schematic of roof- top solar chimney [34].

Fig. 24. Photograph of the Sreejaya and Al-Kayeim prototype [35].

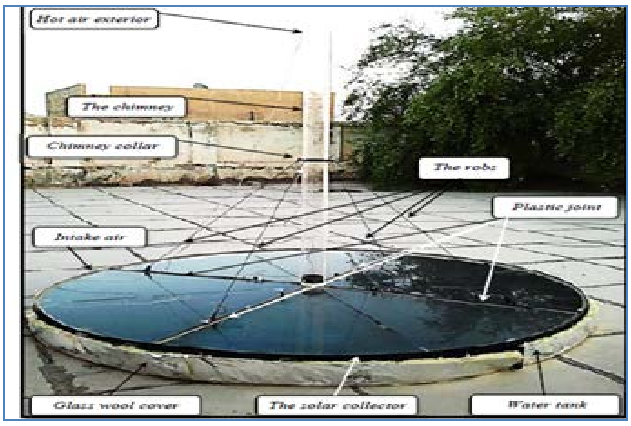

Fig. 25. Photograph of the experimental scale model of the solar chimney power plant by Hiader [36].

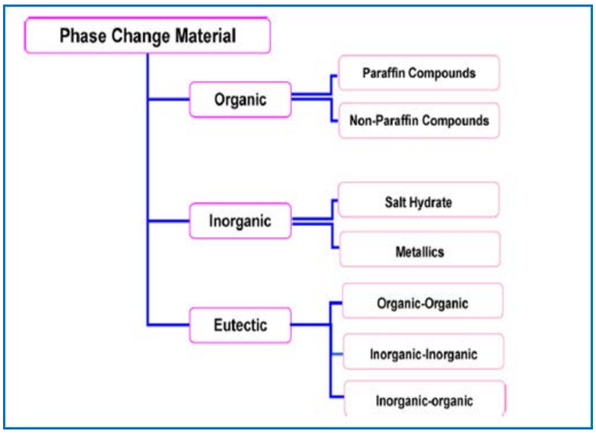

Fig. 26. Classification of PCMs [37], [39].

2.2. Latent Heat Storage

2.2.1 Latent heat storage materials

Latent heat storage materials (LHS) is based on the heat absorption or release when a storage materials undergoes a phase change from solid to liquid or liquid to gas or vice versa, with no change in temperature. When LHS is used to store solar energy it can increase the thermal storage efficiency for the system .Calcium chloride hexahydrate, paraffin wax, sodium sulfate decahydrate (Glauber salt) are the most commonly used as PCMs in solar heating system [37] and the Figure 26, describes the classification of PCMs.

The properties of most commonly latent heat storage materials used in solar chimney applications are discussed in detail below:

2.2.1. a. Sodium sulphate decahydrate (Glauber salt)

Salt hydrates are the oldest and most studied heat storage PCMs. They consist of salt and water, which are combined in a crystalline matrix when the material undergoes solidification. The advantages of Glauber salt are the availability, sharp melting point and high thermal conductivity when compared with other heat storage PCMs. This will facilitate heat transfer in and out of a storage system. They possess a low volume change during phase transformation and also have a high heat of fusion. Thus, reducing the system size and make it easy to design a container that could accommodate volume change. One of the major disadvantages is the possibility to cause corrosion in metal containers which are commonly used in thermal storage system. So, the compatibility between a PCM and its container must be investigated during the design phase of the system. Glauber salt contains 44 % Na_2 SO_4 and 56 % H_2O by weight [37], [38] and Table 4 show the melting point, latent heat of fusion of the salt hydrates.

Table 4. Melting point and heat fusion: salt hydrates [37].

Material	Melting Point (°C)	Latent Heat (kJ/kg)	Group[a]
$K_2HPO_4.6H_2O$	14.0	109	II
$FeBr_3.6H_2O$	21.0	105	II
$Mn(NO_3)_2.6H_2O$	25.5	148	II
$FeBr3.6H_2O$	27.0	105	II
$CaCl_2.1H_2O$	29.8	174	I
$LiNO_3.2H_2O$	30.0	296	I
$LiNO_3.3H_2O$	30	189	I
$Na_2CO_3.10H_2O$	32.0	267	II
$Na_2SO_4.10H_2O$	32.4	241	II
$KFe(SO_4)_2.12H_2O$	33	173	I
$CaBr_2.6H_2O$	34	138	II
$LiBr_2.2H_2O$	34	124	I
$Zn(NO_3)_2.6H_2O$	36.1	134	III
$FeCl_3.6H_2O$	37.0	223	I
$Mn(NO_3)2.4H_2O$	37.1	115	II
$Na_2HPO_4.12H_2O$	40.0	279	II
$CoSO_4.7H_2O$	40.7	170	I
$KF.2H_2O$	42	162	III
$MgI_2.8H_2O$	42	133	III
$CaI_2.6H_2O$	42	162	III
$K_2HPO_4.7H_2O$	45.0	145	II
$Zn(NO_3)_2.4H_2O$	45	110	III
$Mg(NO_3).4H_2O$	47.0	142	II
$Ca(NO_3).4H_2O$	47.0	153	I
$Fe(NO_3)_3.9H_2O$	47	155	I

a- Group I, most promising; group II, promising; group III, less promising- insufficient data.

2.2.1. b. Paraffin wax

Paraffin wax is the most commercially available organic heat storage PCM. The normal Paraffin is of type (CnH2n+ 2) are a family of saturated hydrocarbons with very similar properties. It consists of mainly straight chain hydrocarbons that melt around the range from (23-67°C). Paraffin has been found to exhibit many desirable characteristics as PCMs for storage applications. These are high latent heat of fusion, negligible supercoiling, low vapor pressure in the melting, chemically inert and stable self–nucleating capabilities, no phase segregation, and also commercially available at relatively low cost. However, in spite of their many desirable properties, they have some properties which limit their application. These include large volume change during phase transition and low thermal conductivities. Metallic fillers, metal matrix structures, finned tubes and aluminum powder are all used to improve their thermal conductivity [37], [38]. The physical thermal properties of some paraffin's are shown in Tables 5 and the Table 6 explains the melting point, latent heat of fusion and groups. PCMs are categorized as: (i) group I, the most promising, (ii) group II, promising, and (iii) group III, less promising [37].

Table 5. Physical properties of some paraffin's [37].

Paraffin[a]	Freezing point range (◦C)	Heat of fusion (kJ/kg)	Group[b]
6106	42-44	189	I
P 116[c]	45-48	210	I
5838	48-50	189	I
6035	58-60	189	I
6403	62-64	189	I
6499	66-68	189	I

a- Manufacturer of technical Grade Paraffin's 6106,5838,6035,6403 and 6499: Ter Hell Paraffin Hamburg, FRG.

b – Group I, most promising; group II, promising; group III, less Promising- insufficient data.

c- Manufacturer of Paraffin's P116: Sun Company, USA.

Table 6. Melting point and latent heat of fusion: paraffin [37].

No .of Carbon atoms	Melting point (°C)	Latent heat of fusion (kJ/kg)	Group $
14	5.5	228	I
15	10	205	II
16	16.7	237.1	I
17	21.7	213	II
18	28	244	I
19	32	222	II
20	36.7	246	I
21	40.2	200	II
22	44	249	II
23	47.5	232	II
24	50.6	255	II
25	49.4	238	II
26	56.3	256	II
27	58.8	236	II
28	61.6	253	II
29	63.4	240	II
30	65.4	251	II
31	68	242	II
32	69.5	170	II
33	73.9	268	II
34	75.9	269	II

$ Group I, most promising; group II, promising; group III, less promising- insufficient data.

2.2.2 Experimental and numerical studies for SCPP which utilized PCM as a thermal storage material.

The following literature is a survey by PCM in the SCPP. The review covers the experimental, numerical and mathematical studies.

Sharma *et al.* [39] focuses on available thermal energy storage technology with PCMs for different applications. It mainly focuses on the assessment of thermal properties of various PCMs. Experimental and numerical study was introduced by Yongcai Li *et al.* [40], [41], the thermal behaviors of solar chimney (ventilation types) with PCM under different heat fluxes was investigated and the plant shown in Figure 27. Results showed the absorber surface temperature variations for heat fluxes to be the same during the phase change transition period and the peak thermal efficiencies of solar chimney which were observed to be about 80 % for all cases.

Amori and Mohamad [42] studied the effect of integrating the chimney with paraffin wax on its thermal behavior; heat transfer process and fluid flow in a solar chimney used for natural ventilation under Iraq weather conditions. The experimental prototype explain is shown in Figure 28 were investigated. The experimental result showed the integrated solar chimney with PCM extended the ventilation period after the sunset. Yajuan [43] carried out an experimental work to investigate the enhancement in thermal conductivity and latent heat of paraffin wax. This was obtained by adding compressed expanded natural graphite (CENG); there were five kinds of CENG matrices with different densities which were used to enhance the thermal property of paraffin wax. Results showed that thermal properties of the composites can be 28-180 than that of the pure paraffin wax.

A prototype of solar chimney with Sodium Sulfate Decahydrate as a thermal storage was designed by Kotani [44]. He studied experimentally the effect of the gap between the absorbed plate and the glass cover, air mass flow rate and different atmospheric conditions on the thermal performance, as shown in Figures 29 and 30.

The result showed the integration of PCM inside the solar chimney was positive and it could supply the nearly constant average airflow rate in the evening and at night. Saw *et al.* [45] presented an experimental investigation of a solar collector that integrated PCM with nano-enhanced PCM 20 nm copper nanoparticle added. Results showed that the system was enhanced with the use of PCM and nano-PCM by 6.9% and 8.4%, respectively.

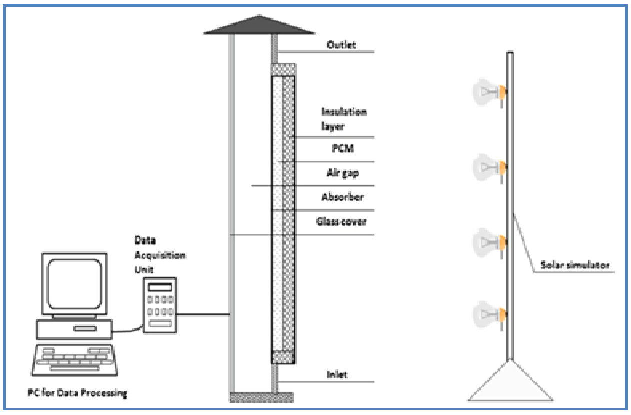

Fig. 27. Schematic of the experimental solar chimney system. (closed model) [40],[41].

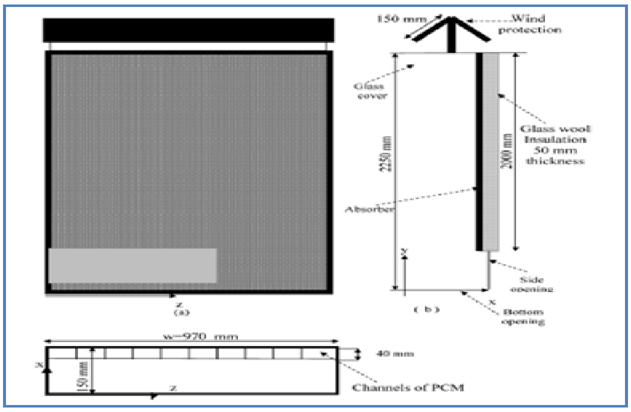

Fig. 28. Experimental test rig (a) front view (b) and (c) top view [42]

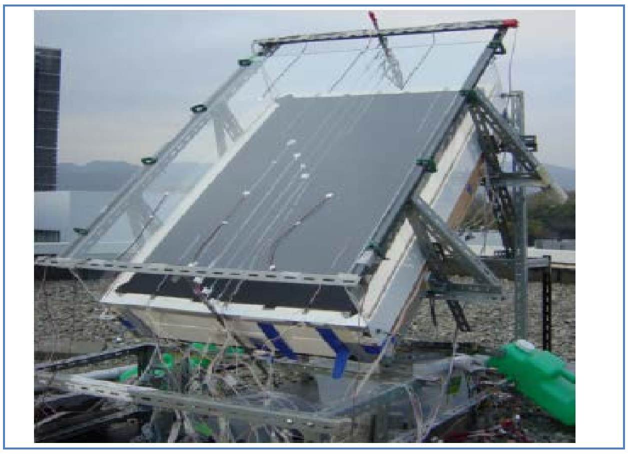
Fig. 29. Photograph of the prototype solar chimney with PCM modules for natural ventilation [44].

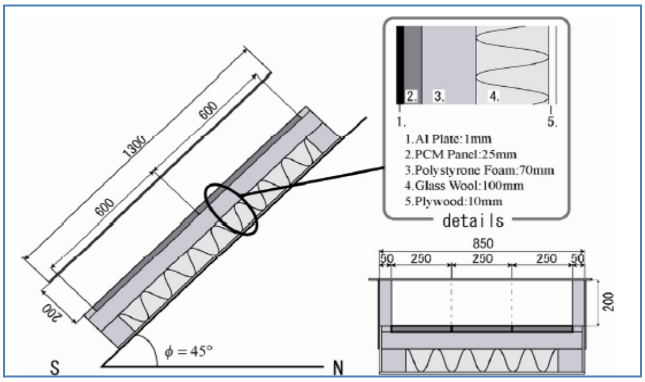

Fig. 30. Cross-sectional view of chimney with built – in PCM storage [44].

The effect of thermal properties of various container materials on the thermal performance of different PCMs was introduced by Sharma *et al.* [37], [46]. The study analyzed thermal conductivity, specific heat and density of the container materials on the melting temperature of the PCM. Thermo physical properties of various heat exchanger container materials are shown in Table 7. [36], [46]. The results of their study are given below:

1- The selection of the thermal conductivity of the heat exchanger container material and effective thermal conductivity of the PCM also very important as these parameters has effect on the melt fraction.

2- As the thermal conductivity of container material increases, time required for complete melting of the PCM decreases.
3- Effect of thickness of heat exchanger container material on melt fraction is in-significant.
4- The initial PCM temperature does not have very important effect on the melt fraction, while the boundary wall temperature plays an important role during the melting process and has a strong effect on the melt fraction [37], [46].

Another parameter that has been considered by various researchers is the shape of the PCM container. Figure 31 shows different paraffin container configurations used as solar thermal storage, as reported by [48]-[50].

Table 7. Thermo physical properties of various container materials [37], [46], [47].

Name of material	Thermal conductivity (W/m ^{0}c)	Density (Kg/m^3)	Specific heat (kJ/kg^{0}C)
Glass	0.78	2700	0.840
Stainless steel	7.7	8010	0.500
Tin	64	7304	0.226
Aluminum	137	2659	0.867
mixed	204	2707	0.896
Aluminum	386	8954	0.383
Copper			

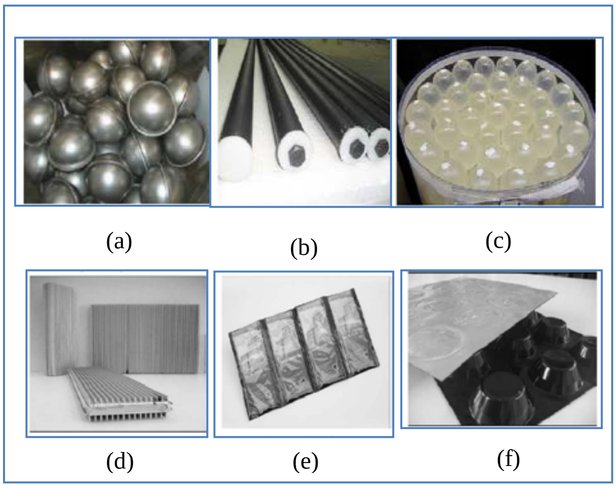

Fig. 31. Paraffin container shapes. (a) Stainless steel ball capsule. (b) Cylindrical capsule. (c) Spherical capsule. (d) Aluminum profiles with fins. (e) Bag capsule. (f) Stripe capsule. [48]-[50].

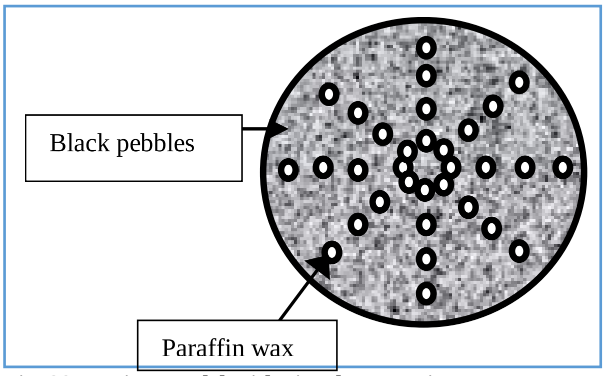

Fig. 32 a. First model with circular containers.

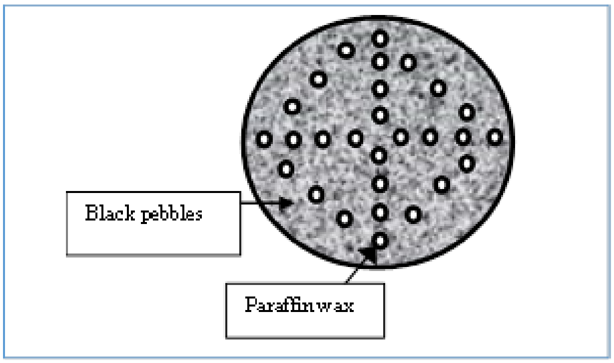

Fig. 32 b. First model with circular containers.

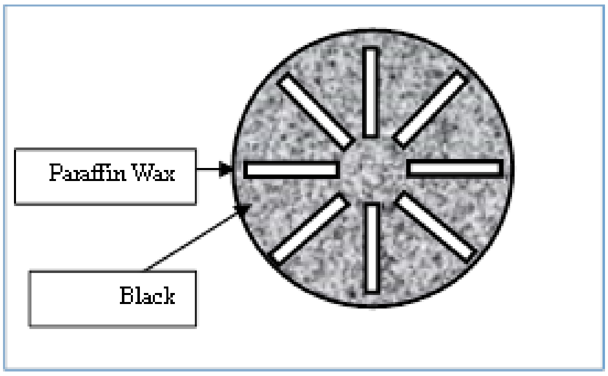

Fig. 33 a. Second model with rectangular containers.

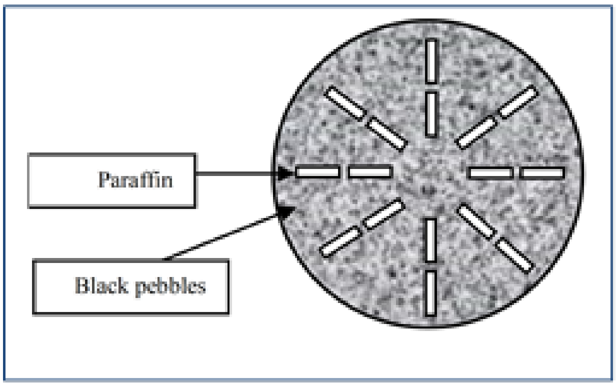

Fig. 33 b. Second model with rectangular containers.

3. DISCUSSION OF THERMAL ENERGY STORAGE TECHNIQUES.

The results obtained from the previous literatures can be summarized as follows:

1- The studies refers to the main effect parameters to select the thermal storage medium are the absorptivity factor and storage capacity of the material.

2- The current thermal storage techniques relied on the usage of one or more sensible thermal storage materials, or using the PCM as a thermal medium storage into SCPP.

3- The advantage and disadvantage of each thermal storage technique in the SCPP can be explained in the Table 8.

Table 8. Advantage and disadvantage of different thermal storage techniques utilized in SCPP.

Type of thermal storage techniques	Calcification of materials	Advantage	Disadvantage
Sensible thermal storage	Natural materials	Soil, stone, and pebbles are most commonly used techniques. Which causing decline the installation cost of SCPP.	Low thermal storage capacity.
Sensible thermal storage	Industrial materials	High thermal storage capacity compare with natural materials	Asphalt, concrete and thermal absorber plates are the most material used in these techniques and results high investment cost to create a large –scale power plant.
Sensible thermal storage	Hybrid Solid – Liquid materials	- Laying of closed water-filled tubes down in nature soil as a thermal storage. - Improve the performance and able the solar chimney to produce power at night.	The lack of water, especially in the desert regions will determine this technique.
Latent thermal storage	Phase Change materials	Paraffin wax is the most commonly used materials as latent heat storage in SCPP which enable the SCPP to operate during the night.	Paraffin wax has low thermal conductivity and hence, metallic fillers, metal matrix structures and nano- materials are all used to increase their thermal conductivity.

4. THE PROPOSED MODEL OF THERMAL STORAGE ENERGY

The present study has proposed to use hybrid sensible-latent techniques as a thermal storage in the solar chimney power plant. Natural materials such as the black stone or black pebbles with paraffin wax are common thermal storage materials that can be used in this proposed model.

Highly effective storage in daytime and releases the heat at particular time such as in the night by paraffin wax, good absorbency and low investment cost of the stone , all these advantages can be achieved when this materials as a hybrid thermal energy storage is used. This proposed type of solar collector will be convenient in the hot-climate regions or all application that cannot used the water bags as a thermal storage. Many geometrical forms of paraffin wax distribution can be installed inside the collector, such as a circular capsule (Figure 32 a, b) or rectangular containers (Figure 33 a, b).

5. CONCLUSIONS

The Solar chimney power plant is a simple solar thermal power technology, which as all thermal solar system is suffering the unavailability of solar energy during the night and cloudy times. Enhancing the collector performance of the solar chimney by integration with thermal storage has been adopted by many researchers, with different methods. A detailed literature review of thermal storage systems in solar chimney is presented in the paper. The review discusses the principles and characteristics of the solid, liquid and the phase change thermal storage materials used/reported so far, in the integrated solar chimney power plants. The literature survey is showing that the usage of sensible or latent thermal storage techniques provides a good improvement in the plant performance but with some disadvantages. As that, this study introduced a hybrid thermal storage material and this

Proposed technique is found to be the most effective in order to enhance the thermal storage system in the SCPP.

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