REVIEW OF SOLAR AIR HEATERS EMBEDDED WITH PHASE-CHANGE MATERIALS (PCM) FOR BETTER PERFORMANCES

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Abstract: The technology of solar air heating systems is one of the branches that is of great importance in capturing and capitalizing on solar energy. This paper presents a summary of the literature on solar air heating systems embedded with materials that have the ability to retain thermal energy, during periods of maximum intensity of solar radiation and its release, when solar energy is reduced or missing for a period of time. It presents the designed and carried out systems by different researchers and the thermal performances obtained in the period of 2017-2021.

Keywords: energy storage, solar air heater, phase-change material, thermal efficiency, absorption plate, paraffin wax

1. INTRODUCTION

Solar air heating systems are equipment that captures solar energy and transforms it into thermal energy useful either to dry various agricultural commodities or to heat living spaces. The thermal efficiency of solar air panels is generally lower due to the temperature transfer characteristics between the air and the material that retains the radiant energy, whose transfer capacity is low. In order to refine the performance of solar air panels, in terms of temperature, the heat transfer coefficient must be increased. The method of implementation of an air jet is an effective approximation to the increase in the coefficient of heat transfer [1].

The prime constituents of a solar air heater, exposed in Figure1, are the plate that absorbs radiant energy, a layer that covers the absorbent plate and insulation. The absorbent material must be resistant to corrosion, have high conductivity and resistance to compressive forces. The preferred material for absorbent plate is copper. The layer covering the absorbent plate must protect against direct contact with objects in the environment, reduce thermal losses to the outside environment and transmit as much heat as possible to the absorbent plate, it can be glass or plexiglass. Insulation, in most cases glass wool, protects the absorbent plate from heat loss through convection and conduction [1].

Solar panels are classified into two categories [1]:

- by type of air movement: passive, active or hybrid;
- according to the direction of air movement: parallel or against the current.

The meteorological indexes that influence the efficiency of a solar air panel are solar radiance, ambient temperature and wind speed. For the implementation of solar radiation, mathematical models of hourly radiation can be realized with software's like MATLAB. A well-known program to conduct CFD simulations is Ansys Fluent which

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performs the computational fluid dynamics simulation in three primary stages: pre-processing, solver, and post-processing. The governing equations used when performing CFD analyses are presented bellow [1].
Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

Momentum equation – X:

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + u\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \tag{2}$$

Momentum equation – Y:

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + v\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right] \tag{3}$$

Momentum equation – Z:

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + w\left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right] \tag{4}$$

Energy equation:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \alpha\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \tag{5}$$

where T and p represents the temperature of the blowing air and pressure and x, y, z are the directions of the u, v, w velocity components [1].

The components of a solar air heater can be visualized in Figure 1 which represents an equipment of this type mounted on the roof of a residential building.

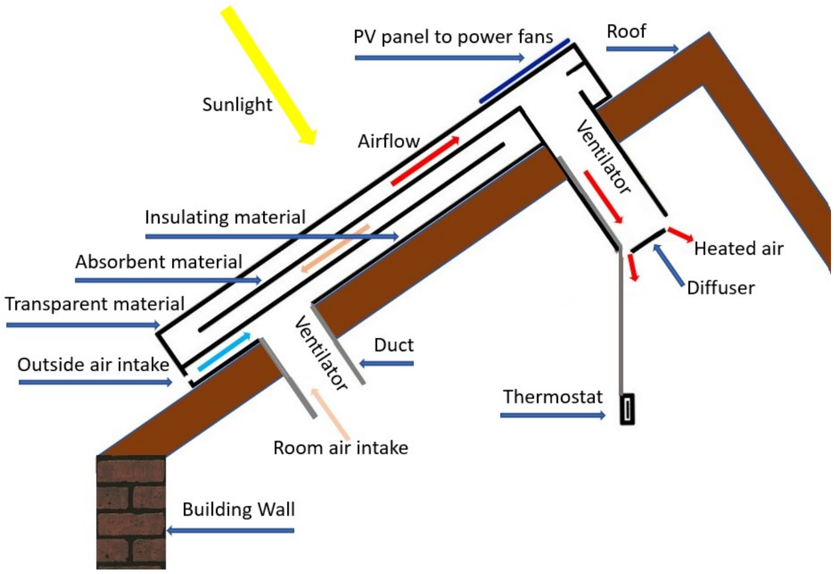


Fig. 1. Solar Air Heater components.

Hot air is used in engineering in various applications such as drying fruits and vegetables or space heating. Solar air heaters are built from components that are worth studying and improving for high performance. An example of a study is the influence of the environment that occurs between the glass covering the panel and the material that absorbs solar radiation, on the mass flow rate and air temperature [2].

For the experimental determination of the impact produced by space on the output of a solar air panel, four models of identical panels were designed and built. The panels are 2 m in length and 0.5 m in width each with a different height between the glass and the absorbent material: 3, 5, 7 and 9 cm. The material that absorbs solar radiation is aluminum with a layer of black paint and the glass covering the panel is 4 mm thick. The panels have an inclination of 40° on the horizon and are located in Tikrit, Iraq. The temperature was measured with type K thermocouples and data was acquired with the Applent AT4808 data logger. The air velocity was recorded with the Benetech GM8 16C anemometer and the solar radiation with the Daystar DS-05 equipment [3].

2. CLASSIFICATION OF SOLAR AIR HEATING SYSTEMS

The following classification is based on the components and modifications made to solar air heating systems to improve capacity. Certainly, various classifications can be done: depending on different changes made to the absorber plate for the most efficacious heat transfer; depending on the applied technics: computational calculus, mathematical or experimental; depending on the purpose of the systems. The classification in this study was realized strictly conformable to the existing studies in the area of solar air heater systems for the considered interval of 2017-2021.

The data extracted from the "Web of Science" source wherein the words "solar air heater" were encountered at least once, was particularly filtered and classified without taking into consideration other classifications. According to the performed filtering, a total of 250 articles worth studying further, were chosen from 1355 publications. The selected articles are the most recent and the rest of the articles that are not on the list dealt with identical topics or could not be part of the realized study even though they are part of the domain of solar air heater systems.

The main classification of solar air heating systems based on the selected items is shown in Figure 2.

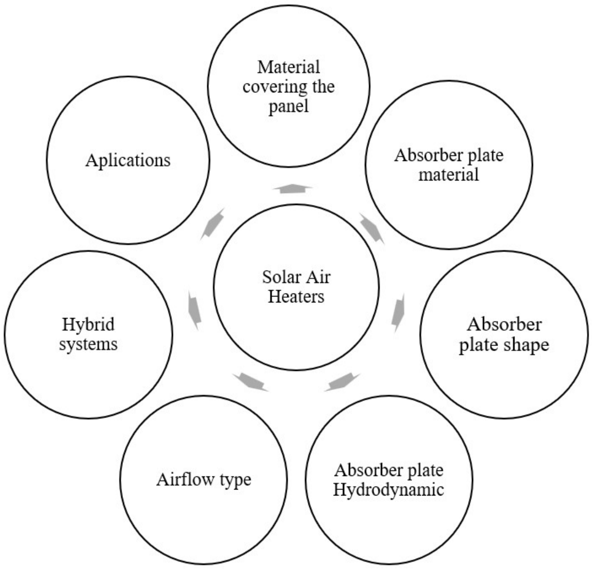


Fig. 2. Main classification of Solar Air Heaters.

For each classification, the analyzed systems are divided into several branches, depending on the methods chosen by the researchers to increase the performance of these energy systems. For the current study in the field of SAHS, related work of the branch containing the absorber plate embedded with PCM is presented.

3. REVIEW OF SOLAR AIR HEATER ABSORBER PLATE EMBEDDED WITH PCM

Applications in which energy storage is included play an important role in the use of solar energy technologies. Currently, the types of applications that emphasize energy storage are very varied. Materials that have the ability to retain and release energy when changing state (PCM) are best suited for storing thermal energy for an extended period of time [4]. For this reason, in the case of applications that include equipment that performs heat transfer, like solar air heaters, it is recommended to use materials with the capacity to change the state with energy release. Although, availability and costs are complex and high, PCM materials are also used in the area of solar air heater systems with the aim of storing thermal energy for a long time and increasing the performance of these systems. The ability to store thermal energy of a solar air heater extends the time of use of the equipment and therefore its performance and efficiencies. As for any equipment when considering SAHs efficiencies we refer to thermal, thermodynamic, effective, energy and exergy efficiencies. If we consider and mount the PCM on the absorber plate as shapes or obstacles we may also refer at friction factor which enhances the amount of thermal energy transferred between the glass and the absorbing surface. The grater the friction factor the more thermal energy is transferred to the fluid and a higher thermal performance is achieved.

In the field of solar air heating systems, PCM materials used for thermal storage were classified as follows: sensitive, latent and thermochemical materials. The obtained classification corresponds to the articles published in the period of 2017-2021 extracted with the help of data academic site "Web of Science" and analyzed individually. The classification of absorbing surfaces with PCM presented in Figure 3 strictly represents the articles published during the analyzed period.

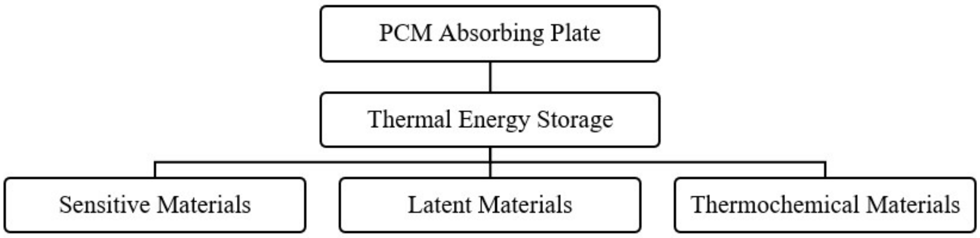


Fig. 3. PCM categories used in the field of SAH for thermal energy storage.

3.1. Sensitive PCM

Sensitive PCMs are materials that retain or release energy through heating or cooling with the help of heat transfer. Typical sensitive materials used in the field of SAHs for the storage and release of thermal energy are shown in Figure 4 and Table 1.

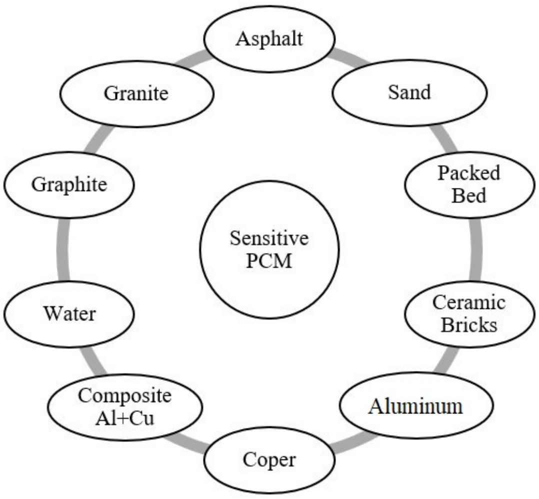


Fig. 4. Sensitive PCM Materials.

Asphalt pavements are accessible infrastructures subject to solar radiation for long periods that often experience fairly high temperatures. Due to the high thermal capacity, asphalt can store sensitive thermal energy in the presence of solar radiation and release it in the absence of solar radiation. Thermal dynamics and efficiency were studied using a solar air heating system consisting of absorption material and storage system using asphalt. The experimentally developed SAH prototype was composed of deflectors, covered with a single bottle and was tested in the presence of two air flows, 0.02 and 0.03 kg/s. The maximum thermal efficiency of the realized and studied system was 80.86% for the air flow of 0.03 kg/s. In conclusion, analyzing the results of the study, the use of asphalt in a solar air heater is a feasible solution that meets the requirements of operation as an absorption material and storage material at the same time [5].

The incorporation of sand grains on the surface of the material that absorbs solar radiation was done to improve the output temperature of a SAH and to determine the thermal efficiency [6]. For the experimental realization and analysis, three different grain sizes of sand were used: 0.075, 0.150 and 0.250 mm and four different air flow rates: 0.010, 0.015, 0.020 and 0.025 kg/s. The results showed improvements of the fluid temperature at the outlet when using the sand compared to a SAH without sand layer on the absorption surface. The maximum energy efficiency of 50.20% was achieved by the solar air heating system where the absorption surface had a layer of 0.075 mm grains of sand and was crossed by an air flow of 0.025. The highest value for effective efficiency, at 42.71%, was recorded for the same air flow, 0.025 kg/s, and for the same grain of sand, 0.075 mm.

The use of full beds is another method of sensitive PCM energy storage in the domain of solar air heater systems. For the theoretical study and analysis of this type of storage system, three different types of materials were used: spherical rock, cast iron and copper. The materials were placed on levels according to their thermal energy storage capacity. Materials with high storage capacity were placed at the entrance of air into the analyzed solar system to realize an efficient charging. In order to evaluate the discharge efficiency of the beds, the exergy analysis of the beds layers build within the system was performed. The following were taken into account: variation in air velocity and fan consumption to obtain a thermal load of 18 kW for a discharge process duration of up to six hours; the effect of the air velocity at the outlet and particle diameters on thermodynamic and thermal performances. The study was conducted using a virtual model and validated with results from the literature of the SAHs field. Thermal energy storage has been improved by 85% and 135% [7].

Solar air heating systems that have a storage system made of ceramic bricks require a means of controlling the air flow to maximize the effectiveness of the storage process [8]. The advantages of using stones or bricks as a thermal energy storage system can be found in the varied range of temperature allowed in operation, low costs, efficient maintenance and simple design. It also offers a certain safety in operation and does not emit harmful gases into the atmosphere. The principle of operation is simple, like terracotta stoves with wood-fired heating. Just as the burning of wood produced thermal energy that was stored for a period of time in the terracotta stove, so the thermal energy acquired with the help of air flow can be transferred to bricks used as a thermal storage system. The disadvantages of a storage system with bricks are the weight and large space necessary to make such equipment. In this case the thermohydraulic efficiency reaches the maximum for precise air flows and specific temperature differences. Thermal efficiency does not occur for the same values as thermohydraulic efficiency on the contrary will increase with increased airflow. Thus, thermohydraulic efficiency is a good indicator of the economic effectiveness of such a process. The maximum thermohydraulic efficiency for this type of storage was 96% for an air flow of 0.0068 m^3/s.

The analysis of a solar air heater combined with a storage system made of aluminum cans was carried out experimentally and computationally [9]. The solar system developed for the experiment consisted of aluminum cans filled with paraffins wax as PCM, a fan mounted at the exit of the system to absorb and achieve a variable flow at the input of the system. To achieve an improvement in the penetration rate of solar radiation, 4 mm glass with low iron in composition of 175 ppm was used. Although the idea of using a lot of PCM material to achieve an advantage in energy storage is plausible, tests have shown that the temperature is high and maintained for a long time when the storage space contained only 33 % paraffins wax in the presence of a 900 W/m^2 solar radiation. Also, exposure for more than 4 hours to a 900 W/m^2 solar radiation brings to the advantage, with higher performance, a percentage of 66% paraffins wax used in the storage system. The percentage of PCM substance used depends on the area, season, location, and user's wishes. The maximum thermal efficiency attained by the system was 57% at an air flow rate of 0.04 kg/s.

Thermodynamic study of a solar system with copper tubes attached to the absorption surface was performed to improve performance. The following have also been studied: energy losses, sustainability index, improvement potential and thermodynamic tests of the system with and without tubes made out of copper. The results concluded with higher exergy and thermal efficiency for copper-tube SAH than a conventional system. The energy efficiency of the copper pipe system varied between 14.53% and 20.36% with an average of 18.26% and of the conventional system had values in the range of 14.45-17.53 with an average of 16.29%. The exergy efficiency had values between 1.2 and 1.939% and an average of 1.69% for copper pipe SAH and values in the range of 0.95-1.53% with an average of 1.41% for the simple system. The airflow for which the tests were performed varied in the range of 0.0166-0.058 kg/s. The highest efficiency for exergy and energy was 5.848% and 62.8% respectively at an air flow rate of 0.05 kg/s [10].

For the solar air heating system with fins and AlCu composite storage material, a CFD analysis was performed [11]. The purpose of this work was to verify, experimentally and with the help of fluid dynamics, the effect of the composite material embedded on the absorption surface on the performance of the analyzed air heating system. CFD analysis and experimental analysis were performed with three configurations of SAHs: aluminum absorption surface with fins; absorption surface with copper layer on top and aluminum fins below; absorption surface with aluminum layer on top and copper fins underneath. As a result of the carried analyses, it was found that the SAH with the absorber plate with copper layer and aluminum fins, compared to the other two configurations, had at the output the highest air temperature of 88°C and high thermal efficiency. The CFD and experimental analyses performed were approximately consistent with an 8% error.

For the analysis of SAH with energy storage in water/ graphite, a CFD simulation was performed [12]. To discretize the governing equations of the 2D model, the finite volume method was used. After solving the equations, it has been found that water can retain thermal energy for up to 4.31 hours and graphite up to 0.46 hours. Also, ten different air flow speeds were used for the study of the performance of solar air heating systems with storage system from water or granite. The results indicated that the speed of airflow present in a solar air heater with a storage system of water/ graphite has a significant effect on the output temperature and the period of operation during the night.

Due to its thermal properties, availability and relatively low price, the use of granite as a storage bed is somewhat justified. The experimental work consisted of combining a concentrating solar system and a bed storage system with rocks. The final results acquired for 3 months indicated the high performance of the achieved system. Based on the data collected during the analyzed period, a model of the system was simulated over a period of one year to verify the long-term performance of the granite storage system. The results obtained from the simulation of the designed model led to the conclusion that such a system is able to provide thermal comfort to a house for a single family. The proposed granite thermal storage system can be successfully used in both new and existing residential buildings located in places with a moderately cold climate [13].

3.2. Latent PCM

Latent PCMs are substances that change their state at a fixed temperature. In this type of materials thermal energy is stored during the change of state: melting, evaporation, crystallization. Typical latent materials used in the domain of SAHs for the storage and release of thermal energy are shown in Figure 5 and Table 1.

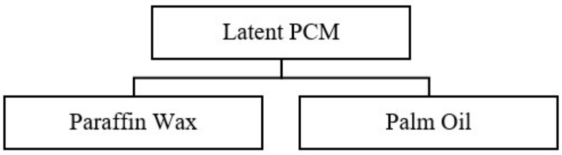


Fig. 5. Sensitive PCM Materials.

Paraffin wax is among the most used materials that when changing the state absorb or release heat energy. The core of an aluminum honeycomb was incorporated with paraffin for numerical and experimental study with the aim of using it as a thermal energy storage structure in a solar air heater system. To solve the governing equations, in the 3D domain, a finite volume method was utilized. The results indicated that this SAH-integrated storage system reduces melting time by over 35%, increases stored energy by up to 50%, and reduces stored energy density by 2%. Using this system, the production of hot air after the sun sets lasts for a longer period [14]. A recent study proposes a solar air heater with thermal storage system (TSSAH) composed of a vacuum glass tube, matrix made of micro-heat pipes and paraffin as a thermal storage material, with a change of state at temperature of 58 degrees Celsius. Due to the low conductivity coefficient of paraffin, fins with openings were used to enhance heat transfer. The maximum thermal efficiency was 77.28% for an 835 W/m^2 solar radiation. During the discharge of thermal energy acquired in the storage system it has been observed that the system can quickly release heat [15]. Another system for storing thermal energy in solar air heating panels relates to the realization of a discrete macro-encapsulated group (rectangular containers) with paraffin wax embedded in the airflow path. A crucial observation from the experiment was that paraffin wax quickly melted at low air flow [16]. The use of a storage system composed of carbon nano-tubes with paraffin wax in stainless steel housing for a solar air heating system has been proposed and analyzed experimentally. The maximum thermal efficiency of the system was 36.4% and the maximum efficiency of the exergy was 84%. In the case of using this system for drying various vegetables and fruits, the results indicated that for increased efficiency it is necessary to increase the amount of material subject to drying [17].

Palm oil was used as a thermal energy storage material in a double-glazed solar system with a flat surface to absorb solar radiation. For this study, in order to highlight the efficiency of palm oil, it was compared to paraffin wax so the authors considered two SAHs, one system with palm oil and the other one with paraffine wax. From the results, it can be concluded that the use of palm oil as a storage medium for solar air heating systems is a good substitute for paraffin, which is a non-renewable environment with future incertitude due to the depletion of global crude oil stocks. From the data of realized tests, average thermal efficiency had a value of 38.4% for paraffin wax storage and 41% for the palm oil thermal storage. Also, the maximum value of thermal efficiency reached 46% for solar air heater with paraffine wax thermal storage and 57.3% was acquired with palm oil thermal storage [18].

3.3. Thermochemical PCM

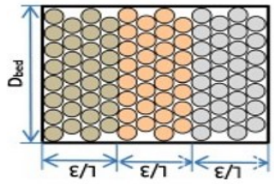
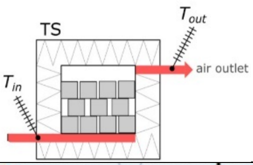
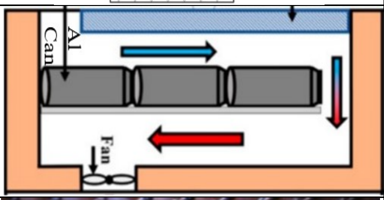
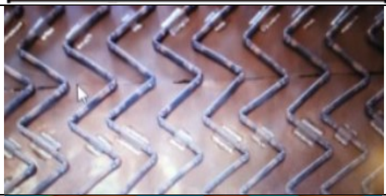
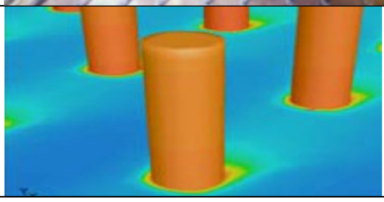
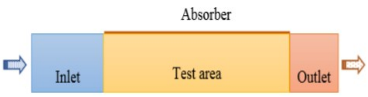
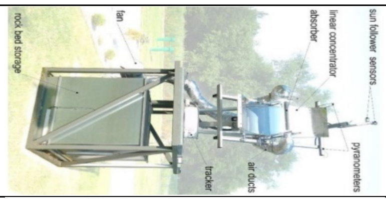
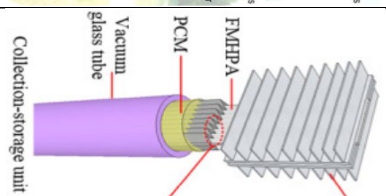
Thermochemical PCMs include sorption and thermochemical reactions. This type of materials stores energy after the dissociation reaction and releases energy through a reverse chemical reaction. Thermochemical storage has the highest storage density, thus allowing the storage of a large amount of energy using small amounts of substances.

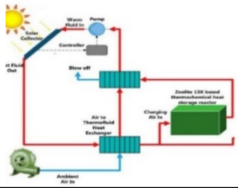
A promising method to store long-term heat is to use thermochemical (TCM). The work presents a design and tested configuration that is based on a reaction between a gas and a solid, between water and zeolite 13XBF to determine the energy storage density and to measure power. The configuration has a volume of 250 liters. To store heat, reversible exothermic and endothermic reactions are used. In a reactor that is filled with dehydrated material, moist air is introduced and heat is obtained through the adsorption of water vapor. This experiment is conducted for hydration-dehydration cycles in the four segments of 62.5 liters, under different conditions, obtaining a power of 4 kW by running the segments in parallel. This system is also capable of producing hot tap water at a temperature of 60°C. With this system that has a segmented reactor concept, a high heat storage performance is achieved. In the work the heat recovery is simulated by a heater. At the material level, an energy density of 198 kWh/m^3 is calculated and at the reactor level an energy density of 108 kWh/m^3 is calculated. For this experiment, without preheating and preheating, the energy density obtained is 61 kWh/m^3. The total efficiency, considered as the energy released during rehydration divided by the energy provided during dehydration, reached 67% [19].

Recent studies are opening up new horizons for thermal storage SAH systems, such as the emergence of nano-embedded PCM materials (NEPCM). One such example is paraffin-based materials in which fractions of 0.5%, 1% and 2% of CeO_2 nano-particles were scattered. NEPCM material containing 1% CeO_2 nano-particles had the best results, energy efficiency of 79.2% and exergy efficiency of 5.1% [20].

Table 1. Solar Air Heaters with absorbing surface embedded with different PCMs.

No.	SAH Type/ Reference	Representation of the system	Operating Parameters	Optimized Parameters	Key Results
1.	SAH with deflectors, single glass and asphalt as PCM [5]		m = 0.02; 0.03 kg/s; I_R = 550; 750 W/m^2.	m = 0.02 kg/s.	Thermal Efficiency: 80%.
2.	SAH with granulated sand as PCM [6]		D = 0.0075; 0.150; 0.250 mm; m = 0.010; 0.015; 0.020; 0.025 kg/s.	m = 0.010; 0.025 kg/s; D = 0.075 mm.	Thermal Efficiency: 50.20%. Effective Efficiency: 42.71%.

3.	SAH with full bed made of spherical rock / cast iron / copper as PCM [7]		u = 0.15; 0.22; 0.25 m/s; t = 7.22; 5.8 h; D = 4; 25 mm.	u = 0.22 m/s; t = 5.8 h; D = 25 mm.	Thermal Efficiency: 85%.
4.	SAH with full bed made of ceramic bricks as PCM [8]		V = 8000 m^3; g = 0.18; 0.20; h = 1÷3 mm; t = 1 h; T1 = 18°C; T2 = 28°C.	Q = 0.5 m^3/s; T = 20; 30°C.	Thermohydraulic Efficiency: 96%.
5.	SAH with aluminum canning as PCM [9]		h = 4 mm; p = 1 atm; T = 30.85; 45.5°C; v = 0.8 m/s;	I_R = 900 W/m^2; T = 45.5°C.	Thermal Efficiency: 57%.
6.	SAH with zigzag copper tube as PCM [10]		m = 0.0166; 0.058 kg/s; T = 31.2 ÷ 36.5°C.	I_R = 649.57 W/m^2; m = 0,05 kg/s.	Energetic Efficiency: 62.8%; Exergy Efficiency: 5.848%.
7.	SAH with fins and composite AlCu as PCM [11]		t = 5; 8 h;	T = 88°C; T_{air} = 83°C; t = 5 h.	Error < 8%.
8.	SAH with water/graphite as PCM [12]		$T_{absorber}$ = 38°K ÷ 32°K; T_{sand} =3 1.71°K	t = 4.31 h; t = 0.46 h;	v = significant effect.
9.	SAH with granite as PCM [13]		m = 2.7*10^{-3} kg/s; T_{amb} = 18 ÷ 21°C.	T_{medium} = 75°C; $T_{absorber}$ = 26°C.	Energetic Efficiency: 70%; Exergy Efficiency: 41%.
10.	SAH with latent energy storage system – paraffin wax [14]		m = 0.02; 0.04 kg/s.	Energy storage increase by 50%; Energy density reduces by 2%.	Thermal Efficiency: 77.28%.
11.	SAH with latent energy storage system – palm oil [18]		T = 23.6°C; 32.4°C; Daily I_R: 11.6; 21.1 MJm^{-2}.	η_a = 46%; η_b = 57.3%.	Thermal Efficiency: 57.3%.

12.	SAH with thermochemica l PCM [19]		V = 250 m^3; P = 3.6 kW; T = 60°C; D = 3.4 mm.	T = 75°C; P = 4 kW.	Total Efficiency: 67%.

4. CONCLUSIONS

Solar air heating systems are a new field not only for many researchers but also for potential buyers who with the help of these systems would have the opportunity to reduce the expenses associated with heating their homes. The total dependence of the SAH systems on the presence of solar radiation limits their operation at locations with the availability of solar energy for as long as possible. Also, day-night variation and areas with cold periods are quite big problems for the field of air heating systems. The thermal performance of SAH, when solar radiation is present, can be improved by modifying the absorption surface and by adding obstacles that create whirlwinds that achieve an efficient heat transfer between the air flow passing through the equipment and its absorption surface. The use of this type of equipment at night or during periods when solar energy is missing implies not only efficiency in capturing as much energy as possible from solar radiation, but also the possibility of storage for as long periods as possible.

Following the summary of this article, paraffin wax used as storage method brought improved thermal performance to solar air heating systems. Thermochemical PCMs are also of high interest due to their storage density, which allows a significant amount of energy to be retained by means of a small amount of substance. An interesting direction and possible subject of study in the field of SAH would be the incorporation of nanotechnology, either in the materials that capture and retain thermal energy or in the air flow realized in the closed circuit, in such systems.

NOMENCLATURE

Table parameters meanings are the following:
I_R – Solar radiation (W/m^2);
Daily I_R – daily radiation (MJm^{-2})
m – Mass flow rate (kg/s);
t – time (h);
v – speed (m/s);
u – superficial velocity (m/s);
T – temperature (°C, K);
D – diameter (mm);
V – volume (m^3);
H – thickness (mm);
g – conversion efficiency;
Q – airflow (m^3/s);
p – pressure (atm);
P – electric power (kW).

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