Review Article

Solar Air Heaters with Thermal Heat Storages

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Solar energy can be converted into different forms of energy, either to thermal energy or to electrical energy. Solar energy is converted directly into electrical power by photovoltaic modules, while solar collector converts solar energy into thermal energy. Solar collector works by absorbing the direct solar radiation and converting it into thermal energy, which can be stored in the form of sensible heat or latent heat or a combination of sensible and latent heats. A theoretical study has been carried out to rate the various thermal energy storage commonly used in solar air heaters. During the investigations rock bed storages have been found to be low type thermal heat storage, while phase change materials have been found to be high heat thermal storages. Besides this, a few other heat storing materials have been studied and discussed for lower to higher ratings in terms of thermal performance purposely for solar heaters.

1. Introduction

Since solar radiation is an inherently time-dependent energy resource, storage of energy is essential if solar is to meet energy needs at night or during daytime periods of cloud cover and make a significant contribution to total energy needs. Since radiant energy can be converted into a variety of forms and feasible to be stored such as; thermal energy, chemical energy, kinetic energy, or potential energy. Generally, the choice of the storage media is related to the end use of the energy and the process employed to meet this application. The optimum capacity of the storage device for a given solar process depends on the time dependence of the solar availability, the nature of the load, the cost of auxiliary energy, and the price of the process components. These factors must all be weighed carefully for a particular application to arrive at the system design (including storage size), which minimizes the final cost of delivering energy [1, 2].

Storage of solar energy is important for the future success of solar energy utilization. The major problem is the selection of materials having suitable thermophysical characteristics in which solar energy in the form of heat can be stored [3]. The materials can be divided into two broad types (Figure 1): those that store energy in the form of sensible heat and those

that undergo a change of state or physical-chemical change at some temperature within the practical range of temperature provided by the solar heat collectors as likely 90 to 120°F [4]. If we talk about the thermal heat storages purposely for solar thermal applications, then (i) SHS: as sensible heat in solids (e.g., rocks, or liquids such as water). The heat storage medium thereby experiences an increase in temperature without undergoing a change in its phase, (ii) LHS: as latent heat of fusion in suitable chemical compounds (e.g., paraffin waxes and inorganic salts). The heat storage medium absorbs the heat added and undergoes a phase transition from the solid to the liquid state at a desired temperature within the operating temperature range [5].

The use of TES systems is essential for solar power systems because of fluctuations in the solar energy input. Several classes of storage may be required for a single installation, depending on the type and scale of the solar power plant itself and the nature of its integration with conventional utility systems. For heating and hot water applications, water and PCMs constitute the principle storage media. Soil, rock and other solids are used as well. Some PCMs are viscous and corrosive and must be segregated within the container in order to be used as a heat transfer medium. A variety of solids are also used; rock particles of 20 to 50 mm in size are

FIGURE 1: Major technique for thermal energy storage at low temperatures.

most prevalent. Well-designed packed rock beds have several desirable characteristics for energy storage. The “ h ” between the air and the solid is high, the cost of the storage material is low, the conductivity of the bed is low when air flow is not present, and a large heat transfer area can be achieved at low cost by reducing the size of particles. TES systems are suggested for storing thermal energy at the medium (38°C – 304°C) and high temperatures (120°C – 566°C). Oil-rock TES, in which the energy is stored in a mixture of oil and rock in a tank, is less expensive than molten nitrate salt TES but is limited to low temperature applications. The selection of the type of TES depends on various factors such as the storage period, economic viability, operating conditions [6]. Both the LHS and SHS or a thermal heat storage with both the properties are used for various solar heating tasks such as solar cooking, solar drying, timber seasoning, and solar space heating. Here, these thermal heat storing materials have been discussed with their thermal properties for solar air heaters (SAHs), which are commonly used for solar drying and space heating.

2. Thermal Heat Storages for Solar Air Heaters

The amount of solar energy striking the earth’s surface depends on the season, local weather conditions, location, and orientation of the surface, but it averages about 1000 W/m^2 (if the absorbing surface is perpendicular to the beam radiation with a clear sky). There are several ways of absorbing and using this free, clean, renewable, and long lasting source of energy. Solar collectors absorb and transfer the energy of the sun to a usable or storable form. Solar thermal collectors can be made in different shapes based on their application. FPCs are the most common types of solar collectors and are usually used as SAH for preheating the air in domestic or industrial heating, ventilation, and air conditioning systems. There are many FPC designs but generally all consist of four major parts: (i) a flat plate absorber, which absorbs the solar energy, (ii) a transparent cover that allows solar energy to pass through and reduces heat loss from the absorber, (iii) a heat-transport fluid (air or water) flowing through the collector to remove heat from the absorber, and (iv) a heat insulating backing [7]. There are different types of solar air heaters that have been developed and can be classified as shown in Figure 2.

FIGURE 2: Classification of solar air heaters.

If we talk about a SAH, then it consists of a flat plate absorber (normally blackened), one inlet duct and one outlet duct for air inlet and exhaust, insulation to reduce heat losses, and a transparent glass cover to incidence the solar radiation inside the heater (or for thermal trap). Auxiliary power can also be used as a supplement to solar energy or to make the solar hybrid system for a continuous and efficient operation. The aim of the study is to find out the most suitable thermal heat storage material for SAHs. There are various designs of SAH among which a few major designs of SAHs with thermal heat storages are discussed as follows.

Lalude and Buchberg [8] have shown the honeycomb-porous bed concept to be an effective means for solar air heating. Design considerations require knowledge of the best cell dimensions and wall coating thickness accounting for collector tilt, time of year, maximum heated air temperature, and T_{amb} . The cost per useful energy collected was minimized for values of wall coating thickness between 0–4 and 0.8 μm , cell depth to spacing ratios between 4 and 10, and cell width to spacing ratios between 7 and 10. A design study of a SAH farm crop-drier system demonstrated a method for the determination of the best values of air temperature, air flows, and solar heater area, to minimize the cost per lb of moisture removal. Jurinak and Abdel-Khalik [9] have presented a simple method for sizing phase change energy storage units (such as $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$, and P116) or rock bed storage for air-based solar heating systems. An effective heat capacity of the phase change unit was obtained as a function of its mass, latent heat, specific heat, and melting temperature. The effective heat capacity can then be used,

along with any convenient design method for systems with sensible heat stores, such as the f -chart method, to estimate the thermal performance of the system utilizing PCES.

Sillman [10] has been used an annual storage with active SAHS to permit storage of summer-time solar heat for winter use. The results of a comprehensive computer simulation study of the performance of active SAHS with long-term hot water storage were presented. A unique feature was the investigation of systems used to supply backup heat to passive solar and energy-conserving buildings and to meet standard heating loads. Results have shown that system performance increases linearly as storage volume increases, up to the point where the storage tank was large enough to store all heat collected in summer. In contrast to diurnal storage systems, systems with annual storage show only slightly diminishing returns as system size increases. Annual storage systems providing nearly 100% solar space heat may cost the same or less per unit heat delivered as a 50% diurnal solar system. Saez and McCoy [11] have developed a mathematical model for simulating the dynamic temperature response of a packed column to an arbitrary time-dependent inlet air temperature. The model includes axial thermal dispersion as well as intra-particle conduction, features that have usually been neglected but can be important in solar energy applications. The results of the model are compared favorably with experimental data found in the literature. The model was used to optimize heat storage in a rock bin (a column packed with pebbles) system subject to a realistic transient inlet temperature.

Bansal et al. [12] have investigated the thermal performance of SAHs consisting of a porous textile absorber between two PVC foils. The η of the heaters depends strongly on the characteristics of the textile forming the absorber and on the back insulation. For an incident solar radiation of 687 W/m^2 at the collector's surface, a temperature rise of $16\text{--}6^\circ\text{C}$ in the air flowing through the solar collector at a rate of $800 \text{ m}^3/\text{h}$ (yielding an η of nearly 71%) was achieved. Further it was found that the linear approximation for the Hottel-Bliss equation leads to erroneous estimations for the collector's parameters when the absorber was porous, for the same type of collector with a denser textile as absorber; however, such an approximation yields, as usual, correct numerical values for the characteristic parameters of the collector. Sodha et al. [13] have proposed and analyzed an air heating system which differs from conventional systems because of having the possibility to be used in the night hours. The system essentially consists of a rectangular metallic (blackened and glazed) tray which was filled with water and air flows in contact with its underside. Explicit expressions were obtained for the parameters describing the system performance in two cases, namely, (a) when the system remains uncovered at all times and (b) when an insulation cover was used at the top to reduce the upward heat losses during off/low sunshine hours.

Bhargava et al. [14] presented an experimental investigation along with a theoretical model of a double-glazed FP-SAH connected in series with an integrated rock bed collector-cum-storage unit. Predictions were made regarding the effects of " h " and number of glazing on the performance of the SAH. The maximum $\eta_{\text{double-glazed}}$ and $\eta_{\text{single-glazed}}$ were

32.6% and 27.1%, respectively. The model was quite fit well with the experimental observations. Garg et al. [15] has modified the theory of a matrix air heater with a rear plate, investigated the role of individual components and studied the performance differences for air flowing downwards and air flowing upwards through the matrix. The system was compared with a SAH of conventional design with flow between 2 plates. The maximum η was 72.19% at $200 (\text{kg m}^{-2} \text{ hr}^{-1})$ of mass flow rate. Sharma et al. [16] have presented an experimental investigation of the enhancement of thermal performance of SAH having its duct packed with blackened wire-screen matrices. Tests were conducted to cover a wide range of influencing parameters including geometry of wire screens, mass flow rates, and input solar energy fluxes under actual outdoor conditions. The effect of these parameters on the thermal performance was investigated and results were compared with those of plane FPCs. The maximum enhancement in η was 55%. Rizzi and Sharma [17] have designed and fabricated a simple solar collector storage (bricks) system integrated with FP-SAH. The objectives were (a) exploring the possibility of using different materials for the insulated base, the transparent coverings, the collecting plate, box structure, potential candidates for SHS, and so forth, (b) to design a suitable medium capacity solar collector storage unit (of water, iron, rock, concrete, brick, Al_2O_3 , etc.), and (c) to discuss the constructional features of the system under investigation.

According to the ASHRAE [18], the generation of thermal energy by solar air heating systems does not always coincide with the energy demand or usage. To accommodate this mismatch between time of generation and use, thermal storage subsystems are required. Storage subsystems function like accumulators, storing excess energy generated by solar energy systems for later usage when solar energy systems are not operating. Thermal storage subsystems also provide interfaces between collector subsystems, space heating, and service water heating systems. When energy usage is matched closely to energy generation, for example, high daytime load for 6 or 7 days per week, minimal or no thermal storage may be acceptable. Abbud et al. [19] have investigated that SAHS at a constant collector outlet temperature of 50°C and 40°C provides 2% to 12% more annual solar heat in a residential building than the same system at conventional constant flow rates. The two modes of operation provided air to the living space at around the same monthly average temperatures of 37°C to 41°C . At constant collector temperature, the heat storage in a "rock bed" avoided the cold and inaccessibility of stored heat commonly encountered with the constant flow rate operation. The constant temperature operation resulted in better temperature stratification in storage than in constant flow systems. The annual solar fraction provided by operating at constant 40°C and full-size (18.53 m^3) rock bed was 0.60, compared with 0.53 for constant flow operation. Decreasing storage volumes reduced solar fractions to the 0.47 levels of constant flow and in 40°C constant temperature. Fath [20] has presented the thermal performance of a simple design SAH. The conventional FP absorber was replaced by a set of tubes filled with a TES (Sunoco-PI16 and Glauber's salt).

The proposed integrated system heat transfer area and “ h ” were increased, and the “ U ” was reduced. Based on a simple transient analysis, explicit expressions for the SAH absorber and glass cover temperatures, effective heat gained, T_o , and the η_{heater} were developed as a function of time. The system showed a 63.35% daily η_{average} (on Sunoco-P116), and the T_o (5°C above T_{amb}) extended for about 16 hrs, as compared to the conventional FP-SAH.

Chauhan et al. [21] have tested a solar dryer (with a capacity of 0.5 tonne/batch) coupled to a rock bed SAH which can be operated even in off-sunshine hours. The SAH was taken 31 cumulative sunshine hours with an air velocity of 250 kg/hm^2 . The heat stored in the rock bed SAH could be used effectively for heating the inlet air for off-sunshine drying. Aboul-Enein et al. [22] have presented a transient model for a FP-SAH with and without thermal storage. Effects of design parameters of the SAH such as length, width, gap spacing between the absorber plate and glass cover, m , and thickness and type of the storage material (sand, granite and water) on the outlet and average temperatures of the flowing air were studied. The T_o of flowing air was found to decrease with increasing gap spacing and m of air. Improvements in the heater performance with storage were achieved at the optimum thickness of the storage material. Therefore, the SAH was used as a heat source for drying agricultural products and the drying process will continue during the night, instead of reabsorption of moisture from the surrounding air. Enibe [23] have been designed and evaluated the performance (on natural convection) of a passive solar powered air heating system which had potential applications in crop drying and poultry egg incubation that consist of single-glazed FPSC integrated with paraffin type PCM heat storage system. The PCM was prepared in modules equispaced across the absorber plate. The system was tested under daytime no-load conditions with a T_{amb} range of 19°C – 41°C and a daily global irradiation range of 4.9 – 19.9 MJ m^{-2} . The peak temperature rise of the heated air was about 15 K, while the maximum airflow rate and peak cumulative useful efficiency were about 0.058 kg s^{-1} and 22%, respectively. Thakur et al. [24] have been carried out some experimental testing on a low porosity packed bed SAH. The packed bed duct had a 2 mm Al sheet several layers of wire mesh screens arranged one above the side of the Al sheet, while below it there was 50 mm of thermocol and 12 mm plywood. The correlations were developed for Colburn J factor and ff for low ranges of porosities from 0.667 to 0.880 and packing a Re range from 182 to 1168. A decrease in porosity was found the factor of increasing volumetric U .

Abbaspour-sani [25] has explained packed bed units as the most suitable storage units for SAHs. In these systems the storage unit receives the heat from the collector during the collection period and discharges the heat to the building in the retrieval process. A method for sizing PBS in an SAHS was represented (Figure 3). The design was based on the K - S curves, which was generated for the storage used in the CSU Solar House-II through simulation. The simulation, with the hourly meteorological data, took into account the principle parameters such as ΔP across the bed, particle

FIGURE 3: Schematic diagram of a simple solar system [25].

diameter, and mean voidage. The results were compared with f -chart analysis. Öztürk and Demirel [26] have investigated the thermal performance of a SAH having its flow channel packed with Raschig rings. The packing improved the heat transfer from the plate to the air flow underneath. The Al absorber plate was coated with black paint. The characteristic diameter of the Raschig rings, made of black polyvinyl chloride (PVC) tube, was 50 mm and the depth of the packed bed in flow channel was 60 mm. The rate of heat recovered from the PB-SAH varied between 9.3 and 151.5 W m^{-2} , while the rate of thermal exergy recovered from the PB-SAH varied between 0.04 and 8.77 W m^{-2} during the charging period. It was found that the average daily net energy and exergy efficiencies were 17.51 and 0.91%, respectively. The energy and exergy efficiencies of the PB-SAH increased as the two of heat transfer fluids increased.

Naphon [27] has studied the heat transfer characteristics and performance of the double-pass FP-SAH with and without porous media. The effect of the thermal conductivity of the porous media on the heat transfer characteristics and performance was considered. The SAH with the porous media gave 25.9% higher η_{therm} than that without porous media. The thermal conductivity of porous media had a significant effect on the thermal performance of the SAH. The model was validated by comparing with the experimental data of previous researchers with average errors of 18.4% and 4.3% for SAH with and without porous media, respectively. Wang et al. [28] have presented a kind of novel high temperature PCM storage heater. A series of experiments were conducted to test the heat charge and discharge performance of this heater. Al Si_{12} was used as a suitable heat storage medium and the air temperature was found near about 135°C . The heater was economical for domestic space heating because of low operating cost. El-Sebaei et al. [29] have investigated the thermal performance of a double glass and double pass SAH with a packed bed. To validate the proposed mathematical model, comparisons between experimental and theoretical results were performed as well as comparisons between the thermal performances of the system without and with the packed bed (above or under the absorber plate) were made.

FIGURE 4: A cross section of the solar air collector with PCM cylinders [30].

FIGURE 5: Wire-mesh packing of the packed bed solar air heater [31].

Some experiments were also performed using iron scraps as a PBM. Values of η_{therm} with gravel were found to be 22–27% higher than those of that without the packed bed. The annual averages of T_{flo} and η_{therm} were found to be 16.5% and 28.5% higher than those in the system without the packed bed, indicating an improvement of the heater performance on using a PBM.

Alkilani et al. [30] have presented a theoretical model of T_o of air due to thermal energy discharge process from a PCM unit that consists of in-line single rows of cylinders containing a compound of paraffin wax with Al powder (Figure 4). The system designed by a single-glazed SAC integrated with a PCM unit which was divided into cylinders as an absorber-container installed in the collector in a cross-flow of pumped air. An indoor simulation supposed that the PCM initially at liquid phase heated by solar simulator, while the pumped air over the cylinders at room temperature, the $\dot{m}$, output air temperature, and the freezing time of PCM; represent important factors 8 steps of $\dot{m}$ were started in 0.05 to 0.19 kg/s.

Prasad et al. [31] have investigated a packed bed SAH using wire mesh as packing material (Figure 5). Data pertaining to heat transfer and friction characteristics were collected for air flow rates ranging from 0.0159 to 0.0347 kg/s·m² for 8 sets of matrices with varying geometrical parameters. The η_{therm} of packed bed SAH was compared with that of conventional SAH to determine the enhancement which was founded in the order of 76.9–89.5%. Experimental data were utilized to develop correlations for Colburn J_h factor and f as a function of geometrical parameters of the bed and the flow Re. The bed with the lowest value of porosity (0.599) has the best η_{therm} lying in between 53.3% and 68.5%. The range of enhancement of η was found to be from 89.5% at minimum of $\dot{m}$ to 76.9% at the maximum $\dot{m}$ in the range of porosity that was investigated.

Singh et al. [32] have discussed a few mathematical models like; 2-phase model (Schumann model), Intraparticle conduction and dispersion model, single phase model, equivalence of 2-phase and single phase models, Cautier and Farber model, Sagara and Nakahara model, and Mumma and Marvin model, in the literature for predicting thermal performance of packed bed energy storage system for SAHs. The paper has shown different models to predict the thermal performance and hence is beneficial to help one to choose a relevant model. Saravanakumar and Mayilsamy [33] have presented the thermal performance of FP-SAH with and without thermal storages. A forced convection solar collector integrated with the different SHS material was developed and tested for its performance. The system consists of a FP-SAH with heat storage unit and a centrifugal blower to increase collector T_o and η (10–20%). Gravel with iron scraps gives better efficiency than other storage materials. Forced convection solar collector was more suitable for drying high quality dried product even in a cloudy climate. Tyagi et al. [34] have presented the performance analysis of a SAH with and without PCM, namely, paraffin wax and hytherm oil. There were three different arrangements, namely, without PCM, with PCM and with hytherm oil, to study the comparative performance of this experimental system. It was found that the T_o in the case with TES was higher than that in the case without TES, besides, the outlet temperature with paraffin wax was slightly greater than that of hytherm oil. It was noted that the η in the case of heat storage was (from 20% to 53%) higher than that in the case without TES, besides the η in the case of the paraffin wax was slightly higher than that in the case the hytherm oil case.

Zhao et al. [35] have developed a model for a SAHS through TRNSYS for a 3319 m² building area. The air heating system had the potential to be applied to space heating in the heating season and hot water supply all year around in North China, by using pebble bed and water storage tank as heat storage. Five different working modes were designed based on different working conditions which were operated through the on/off control of fan and auxiliary heater and through the operation of air dampers manually. Results showed that the designed solar system can meet 32.8% of the thermal energy demand in the heating season and 84.6% of the energy consumption in nonheating season, with a yearly average solar fraction of 53.04%. Alkilani et al. [36] have studied the involvement of the TES to store solar energy for heating air by energy collected from the sun. The review summarized the previous works on SAHs with storage materials include a greenhouse, encapsulation, and the latest development in the solar thermal energy storage with air as a heat transfer fluid. It has appeared that PCM with high latent heat is required for optimum thermal performance of SAH. Dubovsky et al. [37] have presented an analysis of a tubular heat-exchanger which utilizes the latent heat of a PCM. In that, the PCM was melted inside tubes while air flows across the tube banks (Figure 6). The sensible heat capacity of the liquid PCM and the tubes' material was considered small in comparison with the latent heat of melting. An analytical solution was obtained and compared with the results of the numerical solution. Simple formulas were found in the overall heat exchange parameters,

FIGURE 6: Schematic diagram of air PCM heat exchanger [37].

like heat transfer rate, stored energy, and total melting time. The model predicted the results for separate tubes depending on the tube location in the system.

Dolado et al. [38] have tested the thermal cycling of a real-scale PCM (organic and paraffin based) air heat exchanger at T_{amb} . An experimental setup previously designed and used for testing real-scale prototypes of PCM air heat exchangers was modified. The ΔP for the TES unit was measured for 7 different airflows, ranging from 3 to 25 Pa. The analysis of the gathered data accomplishes for developing an empirical model of the unit and for coming to a series of rules of thumbs. An empirical model was developed from the experimental results as a designing tool for applications that use such technology: green housing, curing and drying processes, plant production, HVAC, and free-cooling. Alkilani et al. [39] have discussed that a TES process can reduce the time or rate mismatch between energy supply and energy demand by designing a SAH integrated with pure paraffin wax and paraffin wax-Al composite PCM. The system had a top glazed isolated duct, air pump, and an array of PCM capsules that absorbs the radiation and stores the thermal energy to discharge to demand when there is no radiation. Two cases were tested for storage medium used; the Al mass fraction was 0.5% and the powder particulate size was $70\ \mu\text{m}$. Experimental results indicated that the charging time was reduced around 70% when the paraffin wax-Al composite was used. The η_{TES} reached the maximum magnitudes 71.9 and 77.18% when $\dot{m}$ equals 0.05 and $0.07\ \text{kg sec}^{-1}$ for pure paraffin wax and the compound, respectively. The discharging time was reduced by adding Al powder in the wax. The $\eta_{storage}$ was increased after adding Al powder. Charvat et al. [40] have carried out the simulation studies of the behavior of a SAC with integrated LHS. The model of the collector was created with the use of coupling between TRNSYS-17 and MATLAB. LHS (PCM) was integrated with the solar absorber. The model of the LHS absorber was created in MATLAB and the model of the SAC itself was created in TRNSYS (Type 56). Thermal storage in the form of the PCM led to lower air temperatures at the outlet of the collector during sunshine hours and higher air temperatures after the sunset when the PCM released the heat stored during the day. The simulations were carried out for the PCM with the melting temperature 40°C . Two experimental solar collectors with the parameters similar to those used in the simulations were built and tested.

Krishnananth and Murugavel [41] have fabricated a double pass SAH integrated with TES. Paraffin wax (with Al capsules) was used as a thermal storage medium. The solar heater integrated with thermal storage delivered comparatively high

temperature. The efficiency of the SAH integrated with TES was also higher than that of the air heater without TES. The study concluded that the presence of the thermal storage medium at the absorber plate is the best configuration. Karthikeyan and Velraj [42] have investigated the transient behavior of a packed bed LHS unit, comprised of a cylindrical storage tank filled with PCM encapsulated spherical containers. An enthalpy based numerical model that also accounts for the thermal gradient inside the PCM capsules was developed, and the governing equations were discretised using the explicit finite difference method to solve the temperature distribution of the heat transfer fluid and PCM. It was concluded that for the size of the storage unit selected for the experimental investigation, a heat transfer fluid flow rate of $0.015\ \text{kg/s}$ was able to provide a near uniform heat flow during the charging and discharging processes. The study was good for the design of PCM based TES units with air as the heat transfer fluid, suitable for solar drying and space heating applications. Aissa et al. [43] have studied a forced convection FP-SAH with granite stone storage material bed under the climatic conditions of Egypt-Aswan. Experiments were performed at different air mass flow rates, varying from $0.016\ \text{kg/s}$ to $0.08\ \text{kg/s}$, for five hot summer days of July 2008. The variation of H , η , Nu , and temperature distribution along the air heater was discussed. The results showed an improvement in T_o from 10 to 25°C more than T_{amb} . Tyagi et al. [44] have presented the comparative experimental study based on energy and exergy analyses of a typical SAH collector with and without temporary heat energy storage (THES) material, namely, paraffin wax and hytherm oil. Based on the experimental observations, the 1st law and the 2nd law efficiencies were calculated with respect to the available solar radiation for three different arrangements, namely, one arrangement without TES and two arrangements with THES (namely, hytherm oil and paraffin wax, resp.). It was found that both the efficiencies in case of heat storage material/fluid were significantly higher than those in without THES, besides both the efficiencies in case of paraffin wax were slightly higher than that of hytherm oil case.

Bouadila et al. [45] have conducted some experiments study to evaluate the thermal performance of a new SAH collector using a packed bed of PCM spherical capsules (SN 27) with an LHS system. The solar energy was stored in the packed bed through the diurnal period and extracted at night. The experimental apparatus consists of a packed bed absorber formed of spherical capsules with a black coating and fixed with steel matrix. Capsules had an outer diameter of $0.077\ \text{m}$ and were blown molded from a blend of polyolefin with an average thickness of $0.002\ \text{m}$. The daily η_{energy} varied between 32% and 45%, while the daily η_{exergy} varied between 13% and 25%. Bayrak et al. [46] have studied the performance of porous baffles inserted SAHs using energy and exergy analysis methods. The porous baffles with different thicknesses were used as a passive element inside SAHs. Closed-cell Al foams were chosen as porous materials with a total surface area of $50\ \text{cm}^2$. They were placed sequentially and staggered manner onto the SAH. In the experiments, five types of SAHs were tested and compared with each other in terms of their efficiencies. The measured

parameters were the T_i , T_{out} , T_p , T_{amb} and H . The variation in the efficiencies from case 1 to case 5 was observed from 39.35% to 75.13%. Esakkimuthu et al. [47] have investigated the feasibility of using the PCM (HS-58) in an LHS unit, integrated with a SAH to store the excess energy during peak sunshine hours and also to extend the duration of the utilization of the SAH beyond the sunshine hours, for various mass flow rates. For the storage tank configuration and PCM (HS 58) ball size was considered in the investigation. The η_{SAH} was increased with the increase in the rate of H and found maximum 65% at noon.

Saxena et al. [48] have designed a SAH which can be performed both on solar energy and auxiliary power (Figure 7). The granular carbon (thermal diffusivity ($m^2/s/10^6$)-1.02, emissivity-0.91, absorbitivity-0.97, and pore volume $1.04\text{ cm}^3/\text{g}$) was used as a high heat absorbing material, which was spread in the form of a thin layer and covered with a high resistance float glass to be acting as a absorber tray. The T_p was noticed maximum 68°C with an average output temperature of 57°C on natural convection. While in the case of forced convection, the T_p was observed 46°C maximum with an average output temperature of 33.2°C . Singh and Panwar [49] have explained that the η of energy collection of a FP-SAH is low because of the large thermal losses and low " h " between the absorber and the air flowing in the duct. Packed beds have been successfully employed for the enhancement of the heat transfer coefficients in SAHs and they can be used for drying agricultural products and space heating as well. Theoretical investigation in the effects of thermal conductivity of material and geometry of a screen on the temperature variation in woven wire-screen PB-SAH was also discussed. It was found that the thermal performance depends a few on the thermal conductivity of screen material. Instead, it depends more on the geometry and an extinction coefficient of the matrix. A low value of extinction coefficient is desirable for maximum absorption of solar radiations and minimum thermal losses. The numerical method of analysis used there was based on finite difference approximation and has been solved through a computer program in C^{++} .

3. Result and Discussion

There are many TES materials, available for solar thermal applications among which a few have been investigated by experimental testing previously. Among these materials, the most common materials are the rock beds, pebble beds, Al composites, water, and paraffin wax, which work as SHS, LHS, or both types of the heat storages. The performance comparison of PCM energy storage systems with the water and rock energy storages has shown (Figure 8) that the phase-change energy storage system provides much more effective TES [50]. The experimental testing has been carried to check the feasibility of the different TES materials of storing the heat from the sun during the sunshine hours and releasing of energy in the form of heat during off-sunshine hours purposely in solar energy applications. It has been observed that most of the materials have a good capacity to store the

heat and release this heat (at a desired temperature) up to a long period during off sunshine hours for a heating task. If we talk purposely about TES in solar applications than solar energy can also be stored in insulated vessels of rocks or pebbles, and it is convenient for use in buildings. This type of storage is used very often for temperatures up to 100°C in conjunction with SAHs. For a temperature change of 50°C , rocks and concrete can store up to 36 kJ/kg . Most of the materials proposed for high temperature ($120\text{--}1400^\circ\text{C}$) energy storage are either inorganic salts or metals.

Among the metals, aluminum, magnesium, and zinc have been mentioned as suitable examples. The use of metals media may be advantageous where high thermal conductivity is required and where cost is of secondary priority. If we have a look on the use of these materials in solar energy systems such as solar cooker, solar water heater, solar air heater and solar dryers, then it is notable that these materials make the design complicated and costly (in some cases).

Table 1 shows the characteristics of the most commonly-used thermal storage materials, including sand-rock minerals, concrete, fire bricks, and ferroalloy materials to be used in solar applications. These materials have working temperatures from 150°C to 1100°C and have better thermal conductivities. The materials are all low cost, ranging from $0.05\text{ US\$/kg}$ to $5.00\text{ US\$/kg}$. The only disadvantage is their heat capacities being rather low, ranging from $0.56\text{ kJ/(kg}^\circ\text{C)}$ to $1.3\text{ kJ/(kg}^\circ\text{C)}$, which can make the storage unit quixotically large. The common advantage of SHS is its low cost, ranging from $0.05\text{ US\$/kg}$ to $5.00\text{ US\$/kg}$, compared to the high cost of latent heat storage which usually ranges from $4.28\text{ US\$/kg}$ to $334.00\text{ US\$/kg}$. On the other hand LHS materials (PCMs) can store or release a large amount of heat when reforming their phase structures during melting or solidification processes. Since the phase-transition enthalpies of PCMs are usually much higher (100–200 times) than sensible heat, LHS has much higher storage density than SHS. These materials have phase change temperatures ranging from 100°C to 900°C and latent heat ranging from 124 to 560 kJ/kg . Unlike SHS, in which materials have a large temperature rise/drop when storing/releasing thermal energy, LHS can work in a nearly isothermal way, due to the phase change mechanism. This makes LHS favorable for solar thermal applications, while the most suitable TES materials for solar thermal applications are those materials which can be worked both as SHS and LHS. By using these materials the system performs well in sunshine hours because of higher sensibility and during off sunshine hours just by releasing the heat absorbed throughout sunshine hours. If we go through the best TES material among all of the tested materials then the granular carbon is very economical, easily available, an efficient TES material over other TES materials and the most suitable for solar thermal applications. It is notable that rock bed storage, pebble bed storages, or paraffin wax storages can provide the heat up to 90 minutes after sunshine hours with any additional heat sources, while in the case of granular carbon it has been observed that this TES material successfully maintained the temperature up to 125 minutes in the off sunshine hours (after removing the heat source). Besides this, the range of

TABLE 1: Thermal properties of some commonly used thermal storage materials.

TES	Specific heat	Thermal conductivity	Density	Latent heat of fusion
Rock bed	1	3.26	2240	—
Brick	790	0.90	1920	—
Concrete	840	0.79	1600	—
Pebble bed	0.8 kJ/kg K	2.9 W/m K	1430 kg/m ³	—
Paraffin wax	2.1–8.4 kJ/kg K	24.06×10^{-2} W/m K	920–795 kg/m ³	189 kJ/kg
Hytherm oil	0.73	0.97	725	—
Glauber's salt	2.5	2.25	1330–1460	251
Organic PCM	2	—	800	190
Inorganic PCM	2	—	1600	230
Granular carbon	0.93	0.11	460	—
Water	4178	0.612	998	334
Al composites	0.89	0.21 kJ/ms K	2707	—
Iron gravels	0.56	37	7200	—

FIGURE 7: Solar air heater with granular carbon [48].

temperature fall after removing the heat source (i.e., from full sunshine to off sunshine) is quite low in the case of granular carbon in comparison to other materials.

Apart from this, the suitability of granular carbon to solar thermal applications is purposely good enough in solar cookers and air heaters to obtain and maintain the temperature above the ambient temperature (from 25 to 50°C above T_{amb}). This material has suitable qualities to be used as a TES in solar thermal systems. It is easily available, economical, high heat absorber, light in weight, no leakage problem, no hazard for the system, and efficient for heat storing in poor ambient conditions. If this material is used in SAHs as a TES, then we can get a good temperature for space heating, drying, or timber seasoning.

4. Conclusion

It has been noticed by reading the previous literature thoroughly that every TES has a significant effect on the thermal performance of SAHs. By using those heat storing materials the thermal efficiency can be increased for a good degree of performance of SAHs even in poor ambient conditions. The SHS and LHS are among the major techniques of TES

considered nowadays for different solar thermal applications such as solar cooking, solar drying, timber seasoning and space heating. It can be concluded that the rock bed, brick, concrete, water, and iron gravels are the low rating TES materials for solar applications because of low heat capacity (heat transfer coefficient between the fluid stream and the medium) and low-cost, while the PCMs like paraffin wax and Glauber's salt are useful because of having good capacity to store a comparatively large amount of heat over a slight temperature range, without a corresponding large change in volume during transition, but they are highly costlier over the LHS materials. It is a clear advantage of the latent heat over the sensible heat from the comparison of the volume and mass of the storage unit required for storing a certain amount of heat. Therefore, they can be rated for a higher rating TES material. Besides this, materials which can perform as SHS and LHS are the best suitable for TES in solar thermal applications such as granular carbon. Likely materials can also be rated in the category of high rating material because of high heat capacity and high heat transfer rate as well as the main advantage of the medium that it can perform well in low ambient conditions for solar systems.

A review of SAHs with TES units including space heating systems, solar drying, and timber seasoning with various

FIGURE 8: Performance comparison of PCM, water, and rock storage systems [50].

thermal storage materials has been carried out theoretically. SAHs integrated with various TES materials and heat transfer studies on air as a heat transfer fluid and thermal efficiency have been carried out. It can be concluded from this that the recent researches focused on the utilization on various TES materials, for lower to higher grade TES materials for SAHS. For a better thermal performance of SAH a PCM with high latent heat and with large surface area has been observed for a top rating. While the SHS has been observed to be lower rated, the best rated materials are the combination of LHS and SHS materials like granular carbon and can be categorized as medium rated TES materials. Likely materials are the amalgamation between solar energy group and thermal storage to reduce the heat loss and cost.

Abbreviations

SAH: Solar air heater
 SAHS: Solar air heating systems
 FP: Flat plate
 PCM: Phase change material
 LHS: Latent heat storage
 SHS: Sensible heat storage
 TES: Thermal energy storage
 SAC: Solar air collector
 PB: Packed bed.

Symbols

Re: Reynolds number
 U: Heat loss coefficient

h : Heat transfer coefficient
 ff : Friction factor
 α : Angle of attack
 ΔP : Pressure drop
 $\dot{m}$: Mass flow rate
 η : Efficiency
 T_{amb} : Ambient temperature
 T_o : Outlet temperature
 T_p : Plate temperature
 H, I : Solar radiation.

Conflict of Interests

There is no financial or other relationship with other people or organizations that may inappropriately influence the authors' work and similarly not from the side of the institution.

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