Thermal Energy Storage in Phase Change Material Integrated Solar Collectors for Air Heating Application

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Abstract. Solar energy is an abundant source of renewable energy which can able to support the expansion of energy demand. This review paper represents a complete literature review on recent developments in the phase change material (PCM) based solar collectors for air heating applications such as building heating, greenhouse heating, etc. In this paper thermal efficiency of various types of storage based collector and their performance for air heating (SAH) applications have been discussed. Based on the literature, it has been found that compared to basic solar air heating (SAH) systems, the collector-storage based air heating systems are able to provide higher efficiency with their capacity to recover and utilize the stored heat at night or cold weather conditions. These storage based collectors can be efficiently utilized for applications requiring medium operating temperature range during daytime as well as night times.

1. Introduction

Among all the renewable energy sources available on the earth, solar energy is mostly available. Everyday earth receives a large quantity of solar energy from the sun. Of the total solar energy received by the earth, only a part of it is used by the world in the form of photosynthesis and daylighting and one-third gets reflected into space and the remaining quantity is received by oceans, land, and clouds. Therefore, it is appropriate to collect solar energy and utilize it for the production of electricity, heat and cooling applications. This way of using solar energy for energy production has a nominal impact on the environment without releasing of harmful pollutants into the atmosphere. Also,
apart from the environmental concern, solar energy is also termed as an appropriate source of energy to fill the gap between energy demand and supply due to the depletion of fossil fuels. Many researchers have explored and developed various technologies for the collection and usage of solar energy and still working on various technologies in order to increase the performance of the system [1,2]. Although, there are distinct confronts in the process of collection and storage of solar energy even though it is free. As we know that the availability of solar energy is only during the daytime, it must be collected and stored efficiently to recover and to use at times when solar energy is unavailable. Solar collector converts the absorbed solar energy into thermal energy which is transferred to working fluid. Hence, solar collectors are the principal and very crucial units of any solar thermal energy system. Essentially collectors are of two types, stationary and tracking [2] (Figure 1).

![Figure 1. Types of solar collectors [1]](image-url)

Substantial temperature ranges can be acquired by various collectors such as flat plate solar collector (FPSC) operates in the temperature range of 20-80 °C and evacuated tube solar collector (ETSC) works in the temperature range of 50-200 °C [3,4]. Of all the solar collectors, FPSCs are simple in design, require low maintenance cost, more productive and largely used but delivers less efficiency and outlet temperatures. On the other hand, ETSCs delivers a higher range of outlet temperatures and higher efficiencies compared to FPSCs. Solar collectors are being used for various domestic and industrial applications such as solar water heating [5], solar air heating, solar air conditioning, solar cooking, solar drying, solar desalination [6], steam generation and other applications [7,8]. This paper primarily focused on documentation of recent explorations on the integration of phase change material in the solar collector for air heating applications. Hence, this review primarily explores various storage based collector designs, performance for air heating applications in domestic and industrial sectors and also discussed the aspects that control the efficiency of both collector and LHTES unit, challenges of collector-storage usage along with economic considerations concerning the utilization of collector-storage system for air heating application. Till now, there is no review on collector-storage based air heating systems and according to the author's estimation, this is the first review paper on recent developments in the phase change material based solar collectors for air heating applications.

2. Employment of phase change materials in solar collectors for air heating applications

Air heating is one of the major energy-consuming processes in various applications such as building heating, greenhouse heating, food, textile, paper, pharmaceutical industries, etc. There are various types of collectors available in the market depending on the requirement of the operating temperature range. Since air heating application requires only a medium operating temperature range, that can be fulfilled by FPSCs and ETSCs [9]. Since solar energy is available only during the daytime, so there is
a need for storage of solar energy to utilize during the night time or at a time when solar radiation is unavailable. Solar thermal energy storage systems store solar energy in the form of thermal energy as sensible heat, latent heat or the combination of both. Sensible heat thermal energy storage (SHTES) materials such as water, oils, molten salts, rocks, liquid metals store the thermal energy by raising their temperature. They make use of the heat capacity and change in temperature during the charging and discharging process. The specific heat of the material, temperature change and quantity of storage material determine the quantity of heat stored [10]. SHTES materials are cheap, but its energy density is low and it discharges at varied temperature ranges. Latent heat thermal energy storage (LHTES) materials also called as phase change materials such as mineral salts, paraffin, fatty acids, esters, etc., store/release thermal energy as latent heat based on the absorption or release of heat when it undergoes a phase change from solid-liquid or vice versa [11]. However, compared to the SHTES material, PCM possesses nearly constant operating temperature, high energy storage density and better heat transfer performance which are desirable properties for efficient thermal energy storage. Due to the better thermo-physical properties, phase change materials are utilized in various types of solar collectors to store thermal energy for later use [12]. But one of the major disadvantages with the phase change material is lower thermal conductivity. The thermal conductivity of phase change material can be enhanced by adding highly conductive materials in it [13,14]. Nanoparticles that possess a high thermal conductivity can be immersed in the phase change material which finally forms a novel nanocomposite phase change material with enhanced thermo-physical properties [15,16,17]. By taking advantage of the above-mentioned characteristics of PCM’s, various researchers developed and studied various solar air heating systems by combining solar collectors with the phase change material. Benli et al., 2009; [18] replaced the conventional heating with a PCM (CaCl₂6H₂O) storage unit to provide space heating during the night time or extremely cold days in Turkey. They investigated PCM’s performance by considering the charging and discharging processes and also analyzed 5 different types of 10 solar collector units along with a PCM unit. Solar collector heats the air and then the hot air is passed into the PCM unit where it charged and then enters into the ambient air of the greenhouse. The results disclose that there is acquirement of about 6-9 °C of the temperature difference between inside and outside of the greenhouse and storage based system maintain this temperature difference up to 3-4 hours more than with the usual heating system. This reported that a storage based collector air heating system is very efficient during nights or extremely cold days in Turkey.

![Figure 2. Experimental setup of greenhouse heating system using solar air collectors [18]](image)

Arkar et al., 2005; [19] developed and investigated the performance of air heating system consisting of evacuated tube collectors and Rubitherm PX-21 as phase change material. They experimentally and numerically investigated the process of heat transfer in both collector and LHTES system and conducted the parametric analysis of the whole system for heating of an energy-efficient building which has a large share of passive heating. The evacuated tube solar collector arranged in series-parallel connection with 0.71m² of aperture area was placed on the building’s roof as shown in the fig.3 and the Rubitherm PX-21 PCM with the specific mass of 5.17 kg/m is poured between the tubes of an aluminum concentric-tube whose dimensions are based on the quantity of PCM required.
The whole system showed in fig.4 is arranged in a way that the building’s indoor air is heated up in the collectors and the hot air is made to pass the LHTES system made of concentric tubes where PCM is placed which absorb the heat from the hot air and stored heat as latent heat. Then the cooled air again enters into the collector and the cycle repeats. The latent heat, which is stored in the LHTES system can be utilized during night time for building heating purpose by allowing indoor air directly into the LHTES system by passing the solar collectors which can be repeated in short cycles. In this study quasi-dynamic method was used instead of steady-state method. By validating the experimental results with numerical results, it stated that the mathematical models appropriately specify the conduct of heat transfer in the solar collector. As conduction mode of heat transfer is the governing process in the LHTES concentric-tube as shown in fig.5, they examined heat transfer process mathematically by creating a conduction-dominated model along the unidimensional airflow direction by neglecting conduction along the axial direction due to lower thermal conductivity of PCM and by adopting the explicit method and finite-difference. Due to the microencapsulation of PCM, the convective mode of heat transfer in the liquid phase of PCM is not considered in this study. Using heat capacity method, by considering the PCM’s melting temperature, latent heat and other thermo-physical properties of PCM they plotted the melting and solidification process of PCM. They found the negligible difference between experimentally measured and numerically calculated results. The maximum experimentally measures values of the air inlet, air outlet, PCM inlet, PCM outlet temperature were 73°C, 49°C, 46°C and 33 °C whereas maximum numerically calculated values are 73°C, 47°C, 45°C and 36°C, respectively. This study reveals that of the total produced heat during the daytime was about 54-67% of the recovered heat at the night time for building heating.

**Figure 3.** Evacuated tube solar air collector installed on a building’s roof [19]

**Figure 4.** Solar Collector-LHTES storage system [19]
Belmonte et al., 2016; [20] numerically studied the performance of storage based solar air heating system which is comprised of a solar collector integrated with paraffin wax as PCM (as shown in the fig.6). In comparison to the packed bed of rocks/pebbles which are SHTES materials, phase change material based fluidized bed latent heat storage system charges/discharges faster with high energy density. From the collector, the hot air passes through the LHTES fluidized bed which is sufficient to fluidize the LHTES unit. They analyzed the effect of PCM's melting temperature, capacity of storage, collector’s area, envelope of building on the contribution of solar energy. The results of this study admitted that this type of system is sufficient enough to supply the energy required for the house of a single-family in mild winter. They also found that for the collectors having the areal range of $10$–$20m^2$, the optimal airflow rate of about $100m^3/hm^2$ is appropriate to fluidize $2000$ kg PCM fluidized bed. The TRNSYS simulation results unfolded that a single-family house in regions such as Barcelona and Madrid can utilized this collector-storage system with $2000$ kg of PCM is sufficient to satisfy their $50\%$ daily energy requirement in the mild winter. This type of PCM fluidized bed storage integrated with solar air collector is appropriate to reduce the building heating requirements using solar energy.

![Figure 5. Aluminum Concentric tube LHTES system [19]](image)

In order to increase the share of using solar energy for heating buildings Arkar et al., 2016; [21] developed an air heating system comprising of solar collectors and Rubitherm PX-21 PCM unit which is shown in fig.7. By developing a thermal response model for a building, they numerically studied the system’s design and thermal performance by considering parameters such as solar heating share and solar heat usability. They mentioned that it is mandatory to integrate energy storage system with the solar air heating system of the building. They found that using solar collector which is $1/6th$ of the building floor area integrated with Rubitherm PX-21 as PCM can able to supply $34$ kWh/m2 of energy to the building.

![Figure 6. Solar collector-storage air heating system [20]](image)
Wang et al., 2017; [22] experimentally investigated the performance of a solar air heating system comprised of solar collector with flat micro-heat pipe arrays (FMHPA) and PCM unit which is shown in fig.8. In this study solar collector area of 0.93 m² and Paraffin wax as PCM is considered. During PCM's charging and discharging process, they tracked the distribution of temperature to observe the melting and solidification front. They calculated the efficiency and power during charging and discharging of PCM. This study comes out with a conclusion that of the charging and discharging power level of 393 and 344W, the obtained efficiencies were 59% and 91.6%, respectively. It was found that when the heat transfer fluid's flow rate is increased from 100m³/h and 200m³/h, the heat power of extraction of heat will rise by 10% and 26% respectively and the time of heat extraction will be lowered by 8% and 20%, respectively. There was loss of heat taking place form the glass cover and absorber through convection during charging and during discharging from the insulation through conduction.

Agathokleous et al., 2019; [23] investigated the design and performance of flat plate solar air collector as shown in fig.9. Compared to the current collectors, the uniqueness of this system was embodied by the lesser initial cost and implemented the simple design. This system was well designed to assimilate with the building envelope. Along with energy performance, they also evaluated the economic performance of the system by creating a dynamic simulation model. The results revealed that considered collector having the shortest payback period of 6.2 years.
Khadraoui et al., 2016; [24] analyzed the performance of solar air heating system (SAH) comprising of flat plate solar air collector and paraffin wax PCM unit as shown in fig.10. The SAH system with PCM unit is compared with another SAH without the PCM unit to check the influence of PCM on the performance of the system. The results indicated that due to the presence of PCM unit, there is an increment in the outlet temperature of the SAH system. The daily energy efficiency of the SAH system without PCM and with PCM was 17% and 33%, respectively. They also found that during night time, in the SAH-PCM system there is an increase in outlet temperature of air by 3°C to 7°C compared to the simple SAH system. Also during the night time, due to the elevation of an outlet air temperature of SAH system with PCM, dehumidification of the ambient space taken place by increasing the evaporative capacity of air. This type of system is more favorable for drying purposes at night.

Wang et al., 2017; [25] experimentally studied the performance of SAH system containing vacuum tubes, lauric acid PCM and flat micro-heat pipe arrays (FMHPA) as shown in fig.11. They utilized FMHPA to increase the rate of heat transfer in the system. In this test collector’s, efficiency, PCM’s charging and discharging time were calculated for different airflow rates. The results of their tests concluded that the enhancement in the collector’s efficiency, heat transfer rate and decline of PCM’s charging and discharging time took place at a higher airflow rate. They found that at high airflow rate, active air distribution increases the heat transfer rate, decreases the heat loss and decreases the charging and discharging time by increasing the rate of charging and discharging. At 240 m³/h airflow rate, there is an achievement of the least charging time of 134 min at 682 W instantaneous heat transfer rate and least discharging time of 153 min. During discharging, they found that there is a provision of steady outlet temperature at 60 m³/h airflow rate.
Arfaoui et al., 2017; [26] experimentally studied the performance of solar air heating (SAH) system as shown in fig.12 containing solar air collector and 2-packed bed of (CaCl\(_2\cdot6H_2O\)) PCM spherical capsules aiming to raise the efficiency of the system. During experiments, they took the measurements of solar radiation, wind speed, relative humidity, the temperature of the inlet and outlet air and distribution of PCM packed bed temperature. To evaluate the PCM’s performance they used the measured values and calculated the energy collected, stored and used during the process of charging and discharging of PCM. The SAH-2 packed bed system acquired a daily energy efficiency of 47%. They also found that as the absorbed solar energy increases, there is an increment in the stored heat in PCM during the charging process. During the discharging process for night time, the system discharged 0.3 kW useful heat at a constant outlet air temperature of 27°C. They also found that the system is more productive for night hours during the discharging process by recovering the stored energy.

Abuska et al., 2019; [27] developed a solar air collector combining flat plate solar collector with Rubitherm RT54HC PCM and aluminum honeycomb as shown in fig. 13. They studied the effect of the aluminum honeycomb (PCM’s thermal conductivity enhancer) on the performance of the solar collector-PCM storage system under conditions of natural convection. They compared three different types of collectors which are 26 kg PCM integrated honeycomb collector (type I), a 26 kg PCM integrated collector (type II) and a simple flat plate air collector (type-III). They found that under daylight, the thermal efficiency of type-I, type-II and type-III of solar collectors were 13.6%, 10.9%, and 10.1%, respectively. Therefore, the aluminum honeycomb as a heat transfer enhancer is very
effective, particularly during the discharging process. They also found that compared to type III collector, the energy production in type I and type II continued for a further 469 min and 539 min, respectively.

![Figure 13. Experimental setup of solar air collector [27]](image)

3. Conclusion
This paper offers an outline of the latest investigations on the performance of SAH system by integrating solar collector with the PCM unit and disclosed that this innovative system has vast possibilities in residential, industrial and agricultural sectors. Solar air heating systems have been used for heating energy-efficient buildings, greenhouses, food, paper, timber, and pharmaceutical industries and for many other uses. A collector-storage air heating system is extremely endorsed for medium temperature applications as they can absorb, store solar energy as latent heat during daytime and can recover heat at night or at cold weather conditions. The performance of the SAH system using various PCM based LHTES systems is also presented and found that the storage based collector air heating system responds greatly with the inclusion of PCMs.

Acknowledgements
The authors would like to thank the financial and technical assistance provided by AUN-SEED/Net Japan ASEAN Collaborative Education Programme (JACEP). One of the author (V.V. Tyagi) gratefully acknowledges the PDA grant of Shri Mata Vaishno Devi University Katra.

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