IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 41, No. 5, October, 2023, pp. 1335-1340
Journal homepage: http://iieta.org/journals/ijht

Integration of Solar Flat Plate Collector and Thermal Energy Storage for Heating Applications: An Experimental Study

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https://doi.org/10.18280/ijht.410524

Received: 29 May 2023
Revised: 15 August 2023
Accepted: 15 September 2023
Available online: 31 October 2023

Keywords:
thermal energy storage, solar flat plate collector, phase change material, heat exchanger

ABSTRACT

Efforts to augment the transition from conventional energy sources have encouraged a meticulous investigation into non-conventional alternatives, particularly solar energy for heating applications. This research explores the efficacy of a system integrating a Solar Flat Plate Collector (SFPC) and a Thermal Energy Storage (TES) system in heating applications, thereby offering an innovative solution to contemporary energy challenges. In the proposed system, paraffin wax, functioning as a phase change material (PCM), was utilized in quantities of 100 kg in the SFPC and 200 kg in the TES. The SFPC employed air as the heat transfer fluid, while water was used in the TES. Solar radiation served as the energy source, heating the PCM in the SFPC to a fusion temperature of 35℃. Heat was transported from the SFPC to the TES via the air, enabling effective energy storage. The heating application involved water circulation through the TES. Observations highlighted that the water exiting the TES for heating applications maintained a temperature of 36℃. This outcome demonstrates the potential of the system to heat fluids for various applications as needed, emphasizing its versatility and utility. To ensure the reliability of these findings, a Computational Fluid Dynamics (CFD) analysis was performed, validating the experimental results. The study concludes that the proposed integrated system offers a viable solution for achieving desired fluid heating in diverse applications, thereby reiterating the potential of solar energy in non-conventional heating applications.

1. INTRODUCTION

Sustainable development is the need of the day. As on February 2023, the installed power generation of fossil fuel consumption for India constitute 57.4% and non-fossil fuels 42.6% [1]. Finding new ways of non-conventional energy use will reduce CO_2 emissions. The concept of thermal energy storage (TES) is mainly focusing on storing the heat energy from various waste heat sources and use it for heating or cooling purpose. For different applications, this stored heat could be used viz. pre-heating the milk in the dairy for pasteurization, pre-heating the water and/or air in the industrial boilers, in the neonatal intensive care unit, etc. The design of TES is structured in such a way that it fulfils the requirement of the industry to get a continuous supply of hot fluid in a variable range. Moreover, the pipe arrangement makes the heat to be distributed more evenly and melt the phase change material (PCM) to maximum potential. The unique features of TES system are 24/7 working capability and continuous supply of hot fluid.

TES systems are broadly classified as sensible energy, latent energy and chemical energy. The use of materials for different TES can be in the form of liquid or gas in the sensible state, PCMs in latent state, and different chemicals in chemical systems. In this study latent TES system is selected, as latent heat can store more heat than sensible. The following literature was referred.

In the TES systems various PCMs were studied, as Rakkappan et al. [2] used 1-Decanol as a PCM in the porous structure. It gave an efficiency of 84.99%, 16.33 times higher thermal conductivity. It's use has reduced chilling time by 81.85% to store the thermal energy. Xu et al. [3] have used fatty acid as a PCM, filled in the photovoltaic panel (PV**)**. The results indicated improvement in the thermal efficiency from 5.4% to 22.2%. At 45℃ thermal regulation strategy showed best performance. Sudhakar et al. [4] have presented research on use of PCM with natural water cooling of PV panel. Results showed PV panel cooling enhancement by 11.92% due to use of PCM. Dallaire et al. [5] have done experimental investigation of the building cooling using PCM dual-stack latent TES system. It consists of two PCM stacks placed in parallel. The effectiveness was 89% for perforated plate design and 86% for vertical grills design. Moreno et al. [6] have constructed the constant heat flux PCM wall, whereas outer vertical wall was at a constant temperature. A comparison was made between experimental and numerical data. The results indicated decrease in heat loss by the use of PCM. The comparison gave the reduction of 66.80 to 75.47% Nusselt number. Liang et al. [7] used stainless steel (SS) made pipe for storing the paraffin as a PCM**.** The PCM fusion temperature was at 50℃. The PCM tank was insulated by 50 mm thick polyurethane foam. The study found 5℃ maximum temperature difference during noon and the solar radiation intensity was 769.1 W m^{-2}. The thermal storage efficiency was 81.25%. Pandey et al. [8] have studied PCM in building using energy plus and computational fluid dynamics (CFD) software. The comparison was made between free and forced convection heat transfer. Experimentation revealed with active and forced convection was more effective than passive method. Tunçbilek et al. [9] have done experiment on a wall with PCM. It was found that use of PCM near the exterior did not save energy. Thus, the use of PCM on interior was recommended. The 25℃ optimum phase transition temperature was observed. It saved the energy consumption of room air-conditioner. The result reveals for 23 mm PCM layer, saving in energy by 12.8% as compared to a wall without any PCM. Prabhakar et al. [10] have presented study of PCM use energy storage for building air conditioning during night. The effectiveness improved from 3.32% to 25.62%, when the PCM was used as passive system along with night ventilation and further 40% by using temperature-controlled ventilation. There is scope to integrate the waste heat sources with the TES systems, for PCM heating.

The solar energy is also studied for heating the systems. Miro et al. [11] have combined concentrated solar power (CSP) plants as alternative to electricity with TES. The research work covers impact of use of CSP in TES on the environment. The environmental impact of different TES systems was calculated. The study found that the use of sensible heat system using concrete gave less environmental impact than molten salts. Li et al. [12] have used CSP with PCM capsules for the TES. The effectiveness was twice of non-cascaded PCM-TES system i.e. 84%. The results showed usefulness of different melting temperatures for the various TES-PCM application. Abuska et al. [13] have used aluminum honeycomb structure for latent TES with 26 kg Rubitherm RT54HC grade PCM PCM, in Solar Air Heater (SAH). Solar radiation intensity was as 5.72 kWh m^{-2}, and sunshine duration for August was 11.06 h. It has maintained temperature of space for 4 h after sunset. The efficiency of the system was improved by 10.8 to13.6 %. The 4 cm panels were used for 23.5 kg PCM, mass flow rate of HTF was 65 kg h^{-1}. The SAHs were tested for air velocity from 0.008 to 0.048 kg s^{-1} (Re=962-1925-2888-3851-4814-5776). Three different PCM tanks were selected. The comparison was made between, without PCM, with PCM, and with PCM and honeycomb systems. The HTF velocity was recommended for higher than 0.0323 kg s^{-1}. Liu et al. [14] investigated the use of solar thermal energy and the TES for the cooling, heating and power system. The saving in the energy was found to be 43.1% in summer, 21.1% in winter and 44.9% in transition seasons, which was around 11 percent higher than the other combined cooling and heating power systems. Pirdavari and Hossainpour [15] has developed a cold room to investigate PCM use. The solar refrigeration system was used for cooling the 8640 kg of potatoes stored for intermittent energy availability. For investigation, 9 h of active and 15 h of inactive period was considered for working of the solar refrigeration system. The study has found that PCM could maintain the potatoes at 9℃ during the inactive period of the refrigeration system.

Prakash et al. [16] studied sensible TES with the energy-exergy analysis using double pass SAH with and without the reflector. The materials like Metco and aluminum were used for storing the energy. The double pass SAH with reflector gave more thermal performance than the natural and double pass solar heater. The outlet temperature reached to 60℃ from 36℃. This work could be extended for hybrid systems using suitable PCM. Zhang et al. [17] have studied the use of a part of reheat steam from the intermediate pressure turbine to the TES. The work found 2.56% more efficiency than basic plant with hybrid heat storage. Zhang et al. [18] have investigated integration of TES equipment with building cooling-heating and power system using PCM. The results indicated that both energy storage effectiveness and optimal phase change temperature increased with increasing NTU. Esteves et al. [19] have developed laboratory scale model to study a salt and a paraffin wax as two PCMs. The HTF was oil. Mathematical model gave the heat transfer coefficients between the HTF and the PCM as 132 W m^{-2} K^{-1} for solid state and 1699 W m^{-2} K^{-1} for liquid state. Gil et al. [20] presented TES systems with different storage tanks, heating system and cooling system. During experimentation, two similar storage tanks with shell and tubes HX was used with and without 196 squared fins. Hydroquinone was used as PCM. It has thermodynamic properties like 205 kJ kg^{-1} latent heat and melting temperature between 168℃ and 173℃. The outlet tank temperature was found to be increasing with smaller flow rates in spite of the convective heat transfer coefficient decreasing. Authors suggested scope for PCM tank using fins and variable heat transfer area. Zondag et al. [21] have used in the study shell and tube type HX. It was filled with 142 kg Rubitherm RT™70 PCM. The test was conducted for horizontal and vertical positions. The results reveal a horizontal orientation gave higher charging power than vertical.

The literature review indicates the research gap for integration of solar energy in the TES with HX. This research work aims to design TES system for space heating, which could be used for textile, jaggery furnace etc. applications.

2. METHODOLOGY

TES is a technique used to store energy and use it in the near future for certain applications. It was preferred to use latent heat-based TES system as it can store both sensible and latent heat. The shell and tube type of heat exchanger (HX) was selected as a base to design a TES. A HX with water as a heat transfer fluid (HTF) to the room was selected. The solar heat was used to charge the PCM of the TES. Modelling of HX was carried out using Catia V5 modeling software.

The solar radiations were absorbed by the black coated SS sheet. This heat was transferred to the PCM in the SFPC. The atmospheric air was passed through the SS tubes. This hot air was heating the PCM of the TES. As per the need the water was circulated to heat the room. Thus, during day time the solar heat could be stored in the TES, and at night charged heat could be retrieved.

The CFD analysis of HX was carried out to visualize and better understand the melting of Paraffin wax. Microprocessor based RS 232 digital data logger was used to record real time temperatures of the thermocouples. The discharged heat of PCM was added to the test room for heating purpose.

Following assumptions were considered in the SFPC-TES system:

1. The thermal properties do not change.
2. The heat loss from the system to surrounding viz z viz is negligible.
3. PCM is homogeneous.

3. MATHEMATICAL MODELLING

The SFPC-TES system is shown in Figure 1. It is an assembly of components like HX shell, SFPC pipes, baffles, surge tank, hopper and coil. HX was designed with a capacity of 200 kg of paraffin with heat storage capacity as 28.6 MJ and to have uniform heat distribution. The HTF from SFPC was circulated through the HX tubes. Baffles were designed to provide a firm and rigid support to the pipe cluster, whereas surge tank act as a add on storage option for accumulation of excess wax in case of superfluous expansion of wax.

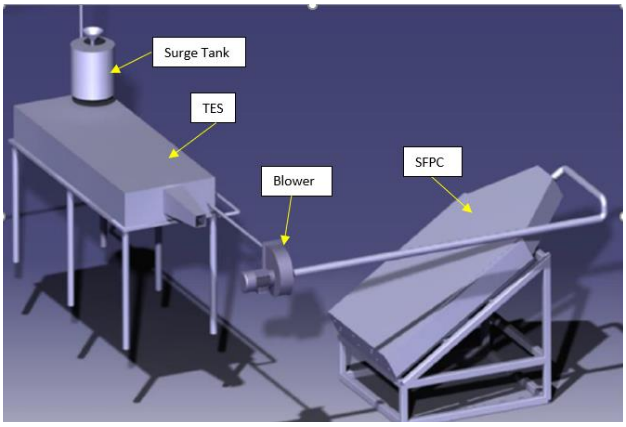

Figure 1. Experimental set up of SFPC-TES

The TES was considered as a reference, so in the SFPC 100 kg of PCM was taken. The heat storage capacity of the SFPC was 14.3 MJ. The overall dimensions of the collected were decided to accumulate 110 kg PCM. The 10 kg volume is kept empty to give recess for expansion of the PCM. Both TES and SFPC were insulated with 50 mm thick insulation of fiber-glass insulation sheets.

The length of the SFPC was decided by using below equation:

Incident radiation on the SFPC: $Q_r = A\, I$

Heat supplied by SFPC: $Q_{SFPC} = m_a\, c_{pa}(T_o - T_i)$

Convective heat addition to PCM: $Q_{PCM} = h\, A\, \Delta T$

where, $\Delta T = T_{bm} - T_s$

$T_{bm} = (T_i + T_o)/2$

It gave the length of the pipe as 156 feet.

The heat storage capacity of HX considering sensible and latent heat for 200 Kg PCM is:

$$Q_{HX} = m_{PCM}[\, c_{PCMs}(T_i - T_{sat}) + h_{sf} + c_{PCMl}\,(T_{sat} - T_o)]$$

Time required to melt PCM by SFPC, $t = Q_{HX} / Q_{SFPC}$.

Thermophysical properties given in Table 1 are used for design of SFPC and TES.

Table 1. Thermophysical properties of paraffin wax

Parameters	Values
Thermal conductivity	0.29 W m^{-1} K^{-1}
Specific heat	2 kJ kg^{-1} K^{-1}
Latent heat	143 kJ Kg^{-1}
Density	870 kg m^{-3}
Melting temperature	35-40°C

4. EXPERIMENTAL SET UP

The experimental set up is composed of TES and SFPC. The technical specifications of the devices used are as mentioned in Table 2.

Table 2. Technical specification of the instruments

Device	Quantity	Make	Range	Accuracy
Anemometer	1	Testo	0.4 to 20 m/s	± 0.1 m/s
Thermocouples	6	K-type	-200°C to 120°C	±0.5°C
Digital data logger (RS 232)	1	Sunpro	16 channels	---

4.1 Details of TES

TES box as shown in Figure 2, was fabricated from AISI304 grade SS material to avoid corrosion. It has size of 1.83 m×0.91 m×0.3 m. Inside this box SS AISI304 pipe of 0.15 m diameter, 47.7 m length was used. The HX pipe arrangement is shown in Figure 3. It has 28.6 MJ heat storage capacity. The HTF was water, which heats the PCM of TES. The surge tank was provided at the top of TES to accumulate expanded PCM. For temperature measurement K-type thermocouples were used. These were attached to the outer side of the pipe. Thus, the interface temperature of pipe and PCM was measured. The temperature of the thermocouples located in the TES-HX were at inlet, at middle of the pipe and at the end as shown in the Figure 3.

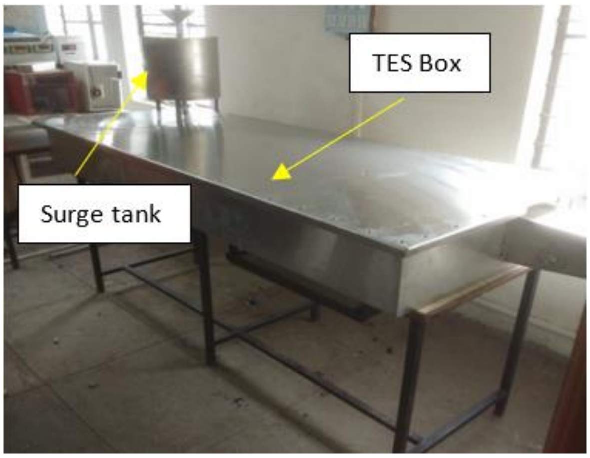

Figure 2. Thermal energy storage box

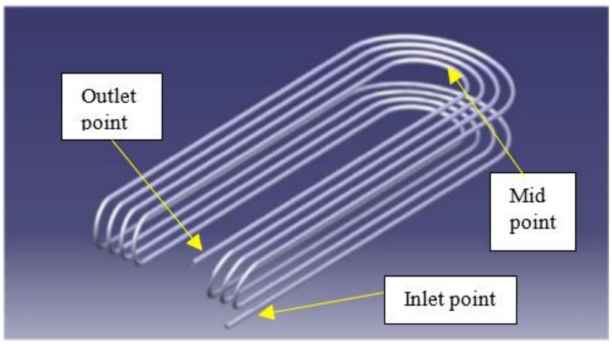

Figure 3. Temperature measuring locations on HX tubing for TES

4.2 Details of SFPC

The SFPC is shown in Figure 4. It was also made of SS AISI304, with 2 mm thickness sheet. The overall dimensions are 1.22 m×0.91 m×0.15 m. The 0.3 m diameter SS AISI304 tubes of 26 numbers were inserted as shown in Figure 5. The upper surface was fitted with toughened glass. The 0.1 m gap was maintained between glass and inner black coated absorber. The absorber was spray painted with black colour having 97% absorptivity. The SFPC was filled with 100 kg of paraffin wax. The air was used as HTF for the SFPC, with velocity of 10 m/s. It was passed through the TES to charge the PCM. To heat the room, the water was used as HTF. It flows through second set of SS tubes. The K-type thermocouples were fitted in SFPC and TES system. The data logger gave the real time temperatures of the thermocouples for every one-minute interval. The SFPC and TES were insulated with 50 mm glass wool insulation to prevent the heat loss to the surroundings. The summary of the setup is given in the Table 3.

Figure 4. Solar flat plate collector at site

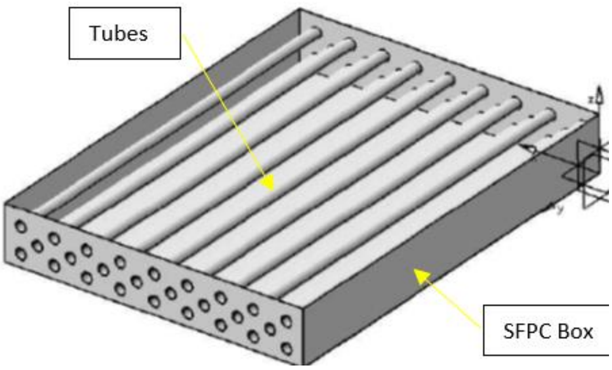

Figure 5. Tube arrangements in SFPC

Table 3. Technical data of SFPC-TES system

Particulars		Specification
SFPC	Weight of PCM filled	100 kg
	Overall dimensions {SS AISI304}	1.22×0.91×0.15 m
	Pipe	0.15 m×1.22 m (26 Nos.)
	Heat storage capacity	14.3 MJ
TES-HX	Weight of PCM filled	200 kg
	Overall dimensions (AISI SS 304, 2 mm thickness)	1.83×0.91×0.3 m
	Heat storage capacity	28.6 MJ

4.3 Uncertainty analysis

The uncertainty analysis as shown in Table 4 is done to show the limitations of the instruments.

Table 4. Uncertainty analysis

Sr. No.	Measurement Error	Value
1	Condenser pressure	0.18
2	Evaporator pressure	0.18
3	Combined thermocouple	0.09

5. RESULTS

Results achieved from theoretical calculations gives us the capacity of TES system collectively as 28.6 MJ. The data logger gave the temperature of thermocouples placed at different locations. The plot of time versus temperature of TES-HX is shown in Figure 6 and plot of temperature versus length of SFPC is shown in Figure 7. It shows the outlet HTF temperature at 36℃ to the test room.

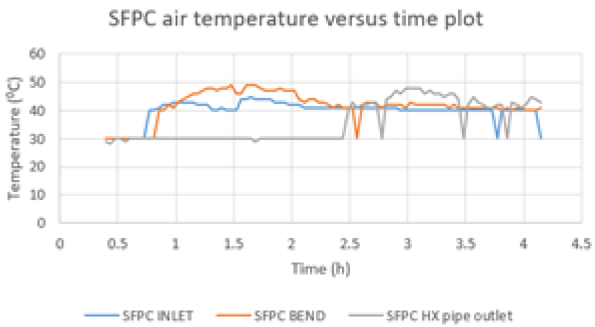

Figure 6. Time vs temperature of SFPC piping

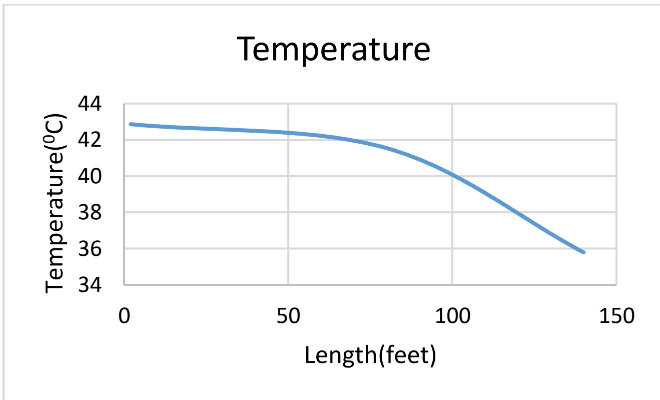

Figure 7. Temperature profile in the TES

5.1 Validation of results

A computational fluid dynamic (CFD) analysis is carried to validate the experimental performance of the TES. It was executed using Ansys, with Simplex method using Green Gauss cell-based method. The pipe walls were mesh interfaced using coupled wall method. The mesh type selection for TES-SFPC and pipe was tetrahedron and quadrilateral respectively. In the mesh model more than 47 lakh elements and 1.5 core nodes were generated. The HX model was designed with the pipe cluster receiving only the hot air from SFPC in operation. The boundary conditions included inlet air velocity at 10 m s^{-1}, air inlet temperature at 55℃, heat transfer coefficient as 55 W $m^{-2}K^{-1}$, outer wall heat flux as 25 Wm^{-2}.

The analysis of the flow through pipe of SFPC is shown in the Figure 8. The PCM was considered initially at 25℃ and HTF at 60℃. It gives outlet temperature of the HTF at an average of 84℃. The experimental HTF outlet temperature was 60℃. The Figure 9 gives the heat distribution in the TES system. The analysis shows 65℃ outlet temperature of the SFPC pipe, whereas the actual temperature was 56℃.

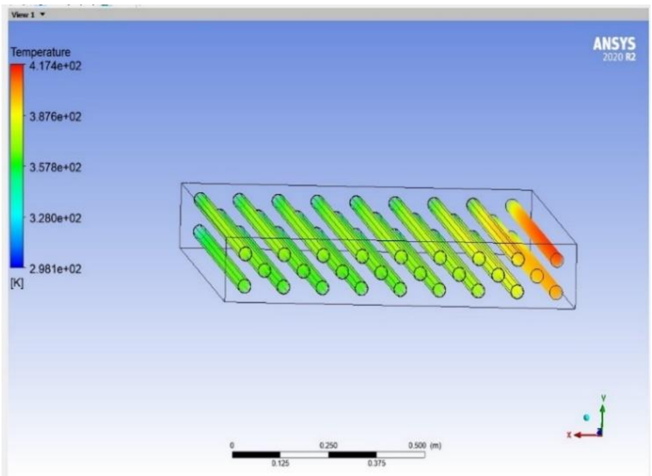

Figure 8. CFD simulation of flow through SFPC

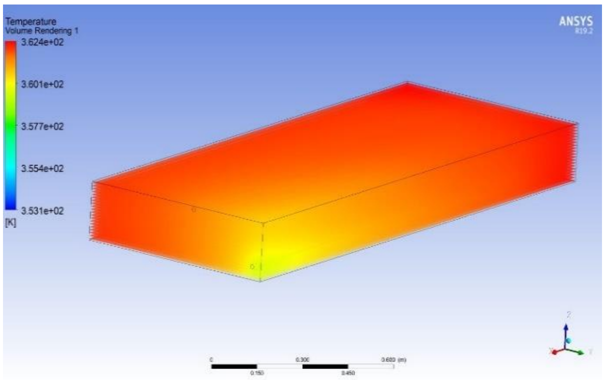

Figure 9. CFD simulation of the TES

6. CONCLUSIONS

An experimental and analytical work on the SFPC-TES was presented. The maximum temperature of HTF of SFPC supplied to the HX was recorded as 55℃, whereas the analytical approach gave 65℃. The 10℃ difference was due to the heat loss. TES could be charged in 7.9 h i.e. approximately in one day time. Thus, the purpose of adding the heat to the testing room was satisfied. The physically recorded room temperature was 36℃. The study recommends use of paraffin wax for heating applications. The HX of TES can be used to store any type of waste heat for heating the PCM. Further research work could be done with different PCM, addition of fillers, and fins on the outer surface of tubes.

ACKNOWLEDGMENT

This research work is carried out of the grants received from Punyashlok Ahilyadevi Holakar Solapur University, Solapur under Breakthrough Research grants (Ref. No.: PAHSVS/S.M.2/2020-21/413, Dated- 16 Jan, 2022). The authors are thankful to the funding Institution.

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NOMENCLATURE

A	Area, m^2
C_{pa}	Specific heat of air, kJ kg^{-1} K^{-1}
C_{PCM}	Specific heat of PCM, kJ kg^{-1} K^{-1}
h_{fPCM}	Latent heat of PCM, kJ kg^{-1}
I	Radiation constant, W m^{-2}
m_a	Mass flow rate of air, kg s^{-1}
m_{PCM}	Mass of PCM, kg
Q_r	Solar radiation, W
Q_{SFPC}	Heat of the solar flat plate collector, W
T_{ai}	Air inlet temperature, ℃
T_{ao}	Air outlet temperature, ℃
T_{wi}	Water inlet temperature, ℃
T_{wo}	Water inlet temperature, ℃
T_{mf}	Mean film temperature, ℃
T_f	Fluid temperature, ℃
T_{sat}	Saturation temperature, ℃
t	Time, s

Subscripts

s	Solid state
l	Liquid state

Abbreviation

CA	Capric acid
CFD	Computational fluid dynamics
CSP	Concentrated solar power
HTF	Heat transfer fluid
HX	Heat exchanger
NTU	Number of transfer unit
PV	Photovoltaic
PCM	Phase change material
SAH	Solar air heater
TES	Thermal energy storage