Experimental Study on the Performance of an Advanced Integral Collector Storage System with Two Types of Phase Change Material Composites

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Abstract

Integral Collector Storage (ICS) systems, combine a water storage tank and a solar collector into one single unit. The technology is very promising, however one of its major drawbacks is heat loss during collection and storage of solar energy. The issue can be addressed by integrating ICS technology with phase changing materials, which have potential to absorb a large amount of heat during the phase transition and therefore minimize temperature fluctuations. However due to the low thermal conductivity of the PCMs and their susceptibility to leakages, their application to ICS is limited. In this work, two different PCM materials with expanded graphite and advanced system structure, were studied in terms of improving ICS performance for residential applications.

Keywords: phase change materials, integral collector storage, flat plate solar collector, expanded graphite

1. Introduction

Solar radiation is one of the major renewable sources of energy in today's world. Solar energy can be captured through a flat plate solar thermal collector. The working principle of a flat plate thermal panel is collecting the solar radiation as it passes through a transparent layer and is drawn by the absorber plate.
The absorbed radiation is then transferred to a medium (e.g. water or air circulating in the tubes) to increase its temperature. The collector housing and the underside of the absorber are insulated in order to minimize the conduction losses (Dabiri, 2016). Typical output temperatures of a flat plate solar collector range between 40°C and 60°C which is most suitable for domestic applications.

As demonstrated by (Kessentini et al., 2011) the major problem with the flat plate solar collector which needs to be addressed, is heat loss from the absorber to the ambient environment. One of the ways to prevent heat losses in the absorber plate is combining it with thermal energy storage (TES).
TES is a technology which allows for accumulation of thermal energy, by heating a storage medium and utilizing the stored energy later. The advantages of using thermal energy storage in renewable energy systems are: 1) an increase in the system's efficiency and reliability; 2) a reduction in the running costs; 3) better pay back periods and a reduction in CO_2 emissions (Dincer Ibrahim & Rosen A. Marc, 2011).

One of the most promising thermal energy storage methods for renewable technologies are phase change materials, which because of their high energy storage capacity became a very potent thermal energy storage system (Whiffen & Riffat, 2013). PCMs are proving to be a good option to economically achieve energy efficiency in buildings (Iten et al., 2016). Phase change materials allow to store large amounts of heat per unit volume during their phase transitions, one of the biggest issues on the way to successfully utilize PCMs as thermal energy storage, is their low thermal conductivity, one of the ways of tackling this issue is mixing PCMs with expanded graphite which provides the composite with good level of heat conductance (Alzoubi, 2015), (Li et al., 2019). PCM/EG composites are very attractive in terms of energy storage capacities and thermal management because of their heat storage characteristics and high thermal conductivity. The use of a composite has a potential to reduce the weight of the thermal storage unit (Zhang & Fang, 2006). Paraffins are ideal to create composites with expanded graphite, because of their safety, high latent heat, non-corrosiveness and stable chemical properties (Shi et al., 2015).

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2. Materials and methodology

2.1 Preparation of a test rig

In order to provide a reference to assess the performance of the developed ICT-PCM system a panel without phase change materials has been tested under lab conditions. The model of the tested solar thermal collector was FKF 200H Al/Cu connected to a coil of a 160l water storage tank, expansion vessel, three speed circulating pumps, a flow meter and a data logger with thermocouples. The solar thermal collector was positioned vertically on a frame, in order to imitate its integration with the front face of a building.

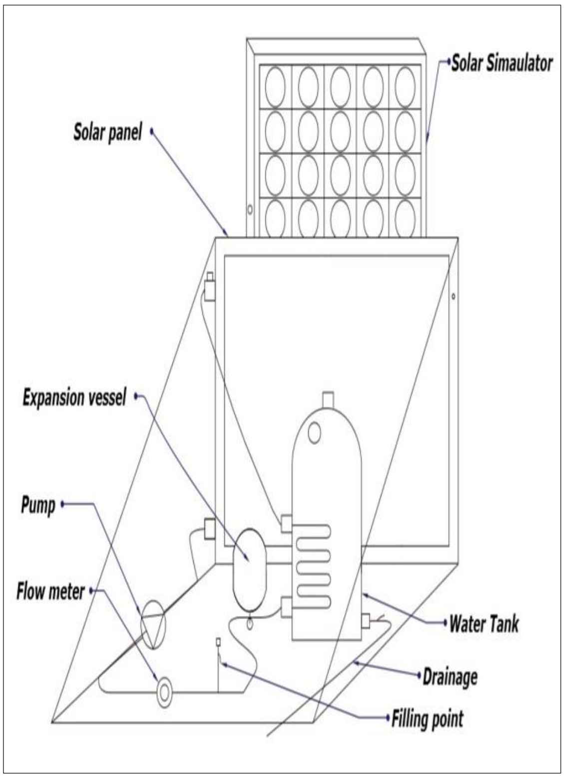

Fig.1: Schematics of a solar thermal system operation

Fig.2: Solar thermal system on a test rig

Because of the unpredictable outdoors conditions the assembled system was placed and tested indoors under a solar simulator which can provide light intensity of up to 1200 Wm^2 (fig.3).

The average irradiation measured with a pyranometer, reaching the front surface of the tested panel ranged between 330 – 360 W/m^2 which can be approximated to a moderate, partially sunny day in the UK and the average water flow rate during the active operation of the system was in the region of 3l / minute.

The testing methodology involved two steps: 1.) warming and passive cooling of the studied panels. During this stage the panels were warmed up both passively (without water circulation) and actively (with the circulating pump switched on). After the simulator was switched off the panels were left to cool down. This test allowed for an initial observation of the heat retrieving potential of the PCM-EG composites.
After the initial stage of the experiment, it was decided to replace the A28/EG composite with an A36/EG, as phase change materials with higher melting points retain heat at higher temperatures which is more suitable for the TES system.

2.) The second step involved testing the amount of heat stored in the PCM composites. It involved passive and active charging of the reference and hybrid PCM panels and then retrieving the stored heat into the water tank. A two-way circulating system explained in chapter (2.4) was developed for the purpose of this test.

The reason for creating the bypass circulation system was the fact that the hybrid ICS – PCM/EG system was converted from the solar thermal panel and it remained with the potential to actively warm up the water inside the tank with open water circulation inside the tanks coil. The focus of this study however was only on the amount of heat which could be stored and retrieved from the collector's thermal energy storage system, and thus bypass circulation was created which allowed to omit the tanks coil during the charging phase of the ICS-PCM/EG panel and then retrieving the stored heat into the tank after switching off the solar simulator.

2.2 Fabrication of the ICS – PCM system

The ICS-PCM system fig. 4 was fabricated for the experimental testing under same test rig and conditions as the reference panel.

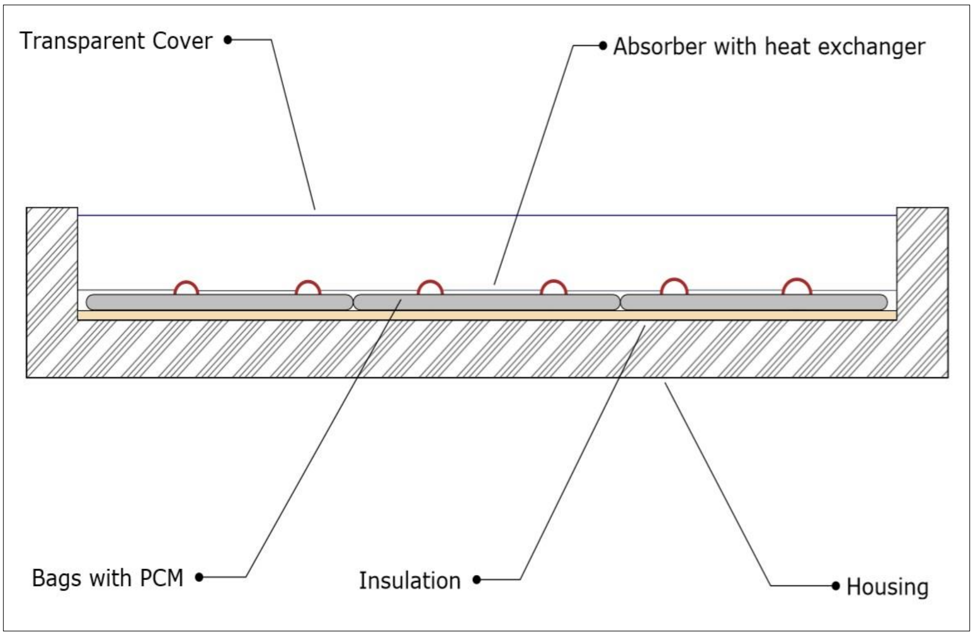

Fig.4: Schematics of a solar collector with PCM/EG

Two types of phase change material composites have been structured and integrated into the solar collector, in close contact with its absorber plate and collector pipes.

2.3. Preparation of the PCM-EG composite

The process of making a composite involved crushing solid PCM material, consisting of 1kg of expanded graphite and 3kg of phase change materials, which were both melted together and stirred until uniformity and placed inside an aluminum bag (fig.5).

(a) *(b)* *(c)*

(d)

Fig. 5: Preparation of a PCM-EG composite: (a) Crushing solid PCM material (b) Pouring graphite into a mixture (c) Stirring until uniformity (d) Placing the composite inside an aluminum bag

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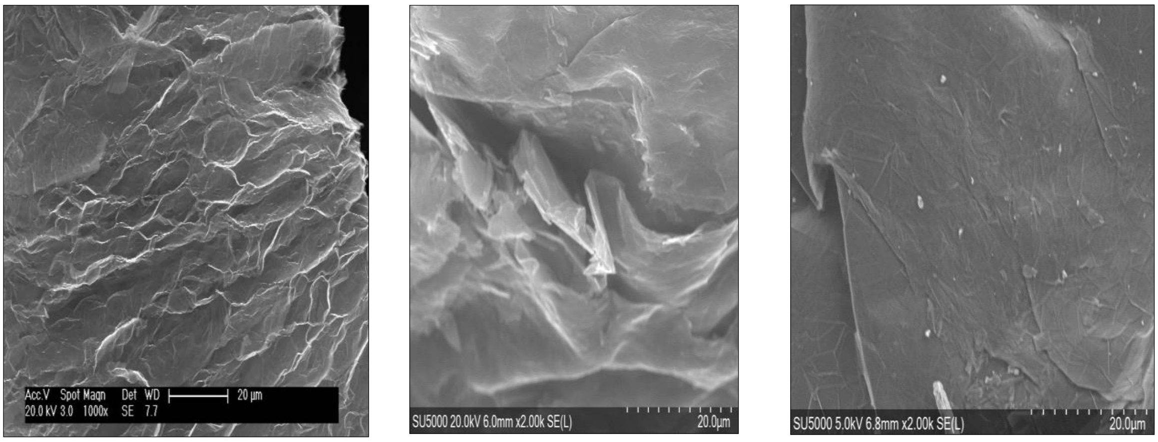
Phase change materials used in the experiment were PlusICE organic A28 and A36 with the properties seen in a table1.

Tab. 1: Properties of A28 and A36 PCMs

PCM type	***Phase change temperature (°C)***	***Density (kg/m^3)***	***Latent Heat Capacity (kJ/kg)***	***Volumetric Heat Capacity (MJ/m^3)***	***Specific Heat Capacity (kJ/kgK)***	***Thermal Conductivity (W/mK)***
A28	28	789	265	209	2.22	0.21
A 36	36	776	250	194	2.3	0.22

The thermal conductivity enhancer used in the study was the SIGRATHERM GFG 600 highly conductive expanded graphite, which was mixed with the PCM material in a 1:3 ratio. Altogether 20 kg of the PCM/EG composite have been prepared and placed in the back of the collector. Below are the pictures made with a scanning electron microscope, figure 6(a) show that expanded graphite has a porous structure which creates a large absorptive area on its surface, BET surface area of EG used in this study is 20 m^2/g. Expanded graphite composites with A28 PCM material fig. 6 (b) appear more smooth and uniform in structure than the EG-A36 composite fig. 6 (c).

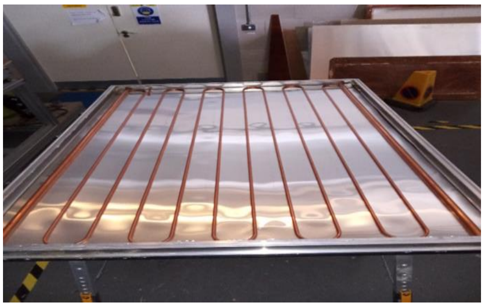


(a) *(b)* *(c)*

Fig. 6: SEM pictures of pure expanded graphite (a) (Shi et al., 2015), A28 (b), A36 (c) PCM/EG composites

2.4. Incorporating PCM/EG composite into a panel

After the PCM/EG composite was prepared and encapsulated in aluminum bags it was then inserted into the back of a panel and then secured with a Quinn Therm insulation and an aluminum cover sheet (fig.7).



(a)

(b)

(c)

(d)

Fig 7: Preparing encapsulated PCM/EG in the back of the panel: (a) heat exchanger with absorber plate (b) encapsulated PCM/EG composites (c) PCM/EG composites covered with Quinn Therm insulation (d) back of the panel covered with an aluminum sheet

2.5. The production of a two-way circulation system

The next stage of the experiment involved producing a two-way circulating system which allowed for water circulation in 2 modes (fig.8).

During the first mode valve 1 is shut and valve 2 is open, this allowed water to circulate inside the panels' heat exchanger, while bypassing the coil of the tank. During this phase the panel was absorbing heat from the solar simulator.

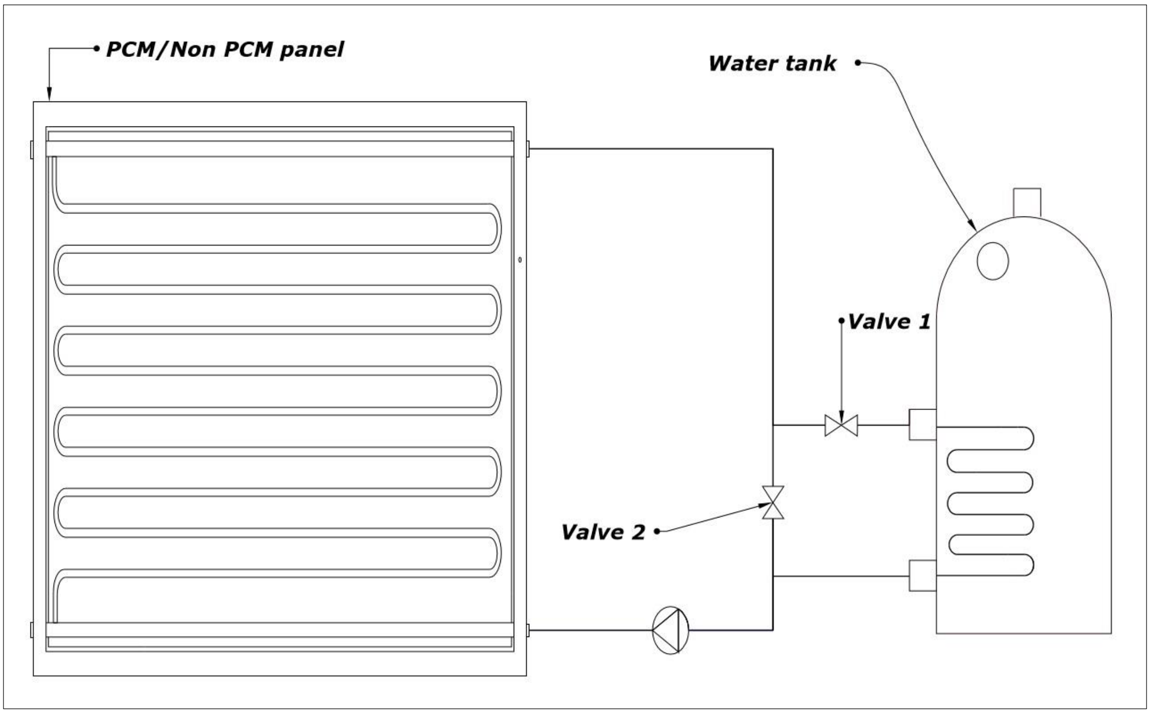


Fig 8: Schematics of a two - way circulation system

During the second mode of the operation, valve 1 was opened and valve 2 was shut which allowed to recover heat stored inside the panel to the water tank. This two-mode operation system enabled the comparison of the amount of heat stored in the panel with and without phase change material composites.

3. Results and analysis

During the first stages of the experiment, a reference panel and a panel with PCM/EG A28 and A36 were tested. The temperature inside the panels was measured on the panels' inlet and outlet.
After being heated, the reference panel cooled down from 44°C to 15°C in 3 hours with an average temperature during the cooling period of 23.15°C. The panel shown a very low heat retention properties because apart from the heat stored in water and piping of the panel, there are no other heat retention mechanisms.

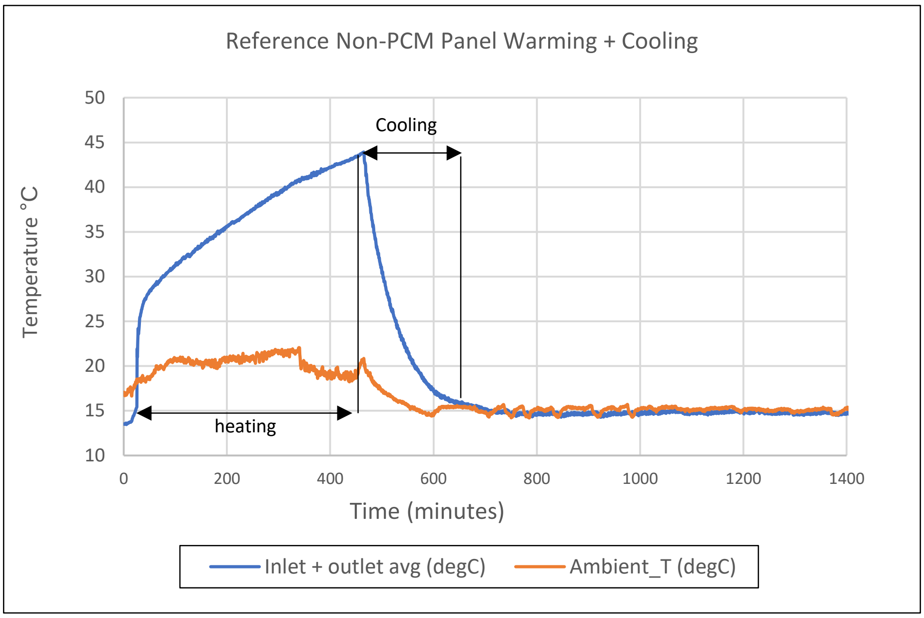


Fig 9: Reference Non – PCM panel warming + cooling

Results obtained from testing the hybrid PCM panel with A28/EG composite show that after the warming period it cooled down passively from 35°C to 19°C in 11 hours with an average temperature during the cooling period of 21.28°C (fig.10).

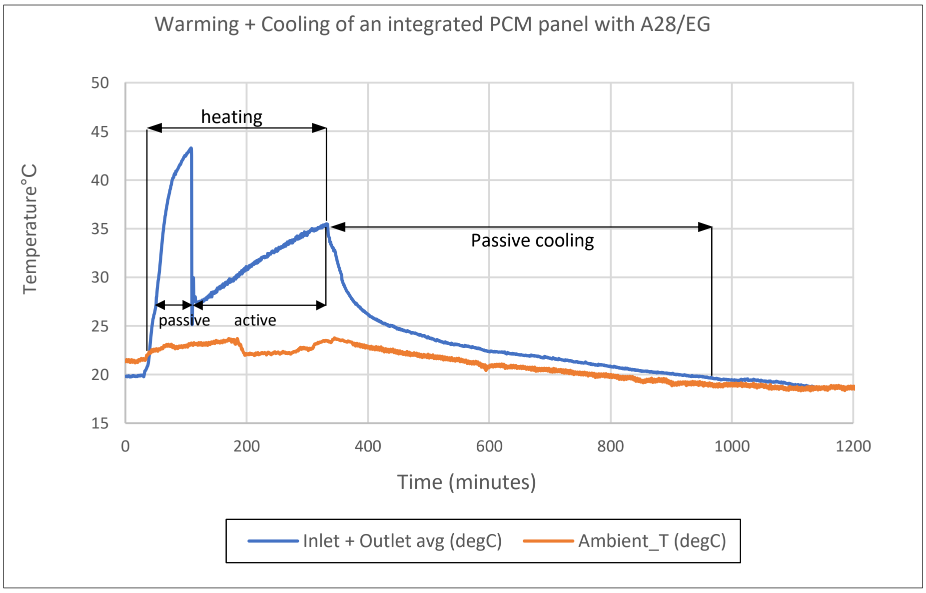


Fig10: PCM panel with A28/EG warming + cooling

The PCM/EG – A36 panel shows a much lower internal heat loss than the reference panel. It took 12 hours and 45 minutes for it to cool down from 42°C to 20°C, with an average temperature during the cooling process of 24.54 °C (fig.11)

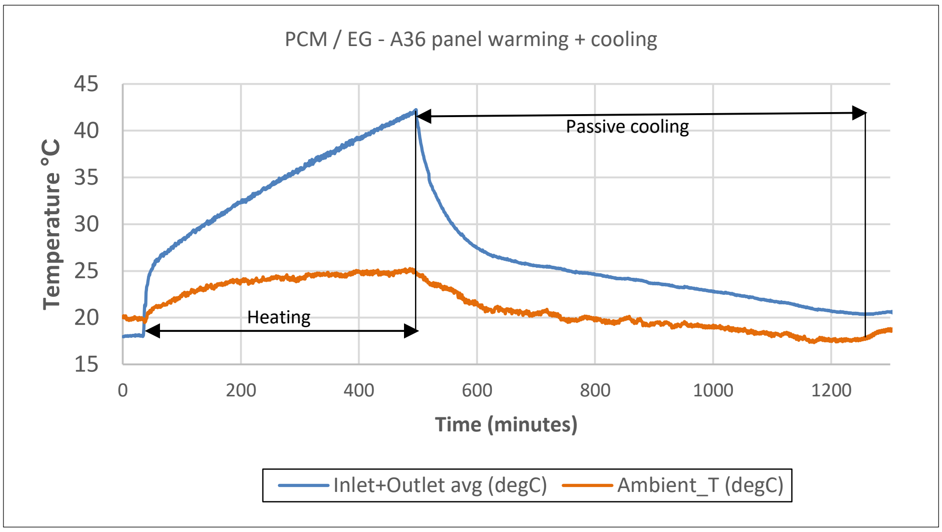
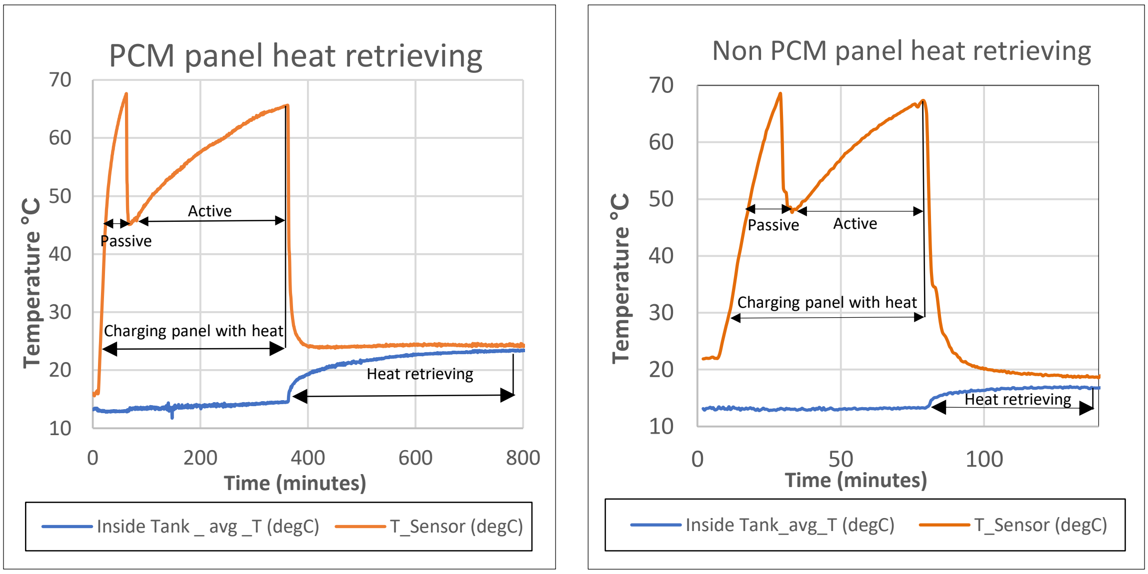


Fig 11: PCM/EG – A36 panel warming + cooling

3.1 Heat retrieving from a PCM and non PCM panel's

During the next phase of the experiment, results from a charging and discharging panel with a two-way operating cycle were obtained (fig.12). Temperature readings were taken from inside the panel's sensor and from within the tank.



(a) (b)

Fig 12 : Heat retrieving: (a) non – PCM reference panel (b) PCM panel

The non PCM panel charged in 60 minutes from 22°C to 67°C whereas the PCM panel was charged in 5 hours 54 minutes from 16°C to 65 °C indicating that PCM materials were absorbing heat for extended period. During the heat retrieving stage, 8.5°C was recovered from the PCM/EG – A36 panel into the tank, and 3.5°C of heat was retrieved from the non PCM panel.

3.2. Calculating the amount of heat retrieved from the PCM and non PCM panels

The amount of heat retrieved into the tank from both panels can be calculated with following equations:

$Q = \rho V C_p (T_f - T_i)$ (eq. 1)

$V_{tank} = \frac{\pi}{4} D^2 H$ (eq. 2)

where:

$\rho_{water} = 997\ {kg}/{m^3}$
$C_{pwater} = 4.2\ kJ/kgK$

Therefore:

$Q_{PCM/EGpanel} = 5151\ kJ$
$Q_{reference\ panel} = 2121\ kJ$

The quantity of heat energy stored in the PCM materials is the difference between heat retrieved from the hybrid PCM panel minus the heat recovered from a reference panel.

Hence:
$Q_{PCM} = 5151$ kJ – 2121 kJ = 3030 kJ = 0.842 kWh

4. Economic and environmental importance

The amount of heat retrieved from the PCMs into the tank after one charging cycle was calculated as (0.842 kWh). If we assume two daily charging and discharging cycles of the PCM-EG panel, it has the potential to reduce the annual cost of water heating by £96 and the CO_2 emissions could be reduced by 141 kg. Although this is a promising initial result, future studies need to focus on increasing the performance of the ICS – PCM/EG system in order to make the technology more sustainable and cost effective.

5. Conclusions

In this study the potential of using the phase change material composites for integral collector storage systems has been investigated. The panels with PCM/EG – A28 and A36 were demonstrated to cool down 8 and 9 hours longer than the reference panel respectively. The amount of heat retrieved to a PCM/EG – A36 panel was 8.5°C as opposing to a 3.5°C retrieved to a tank from a panel without phase change materials.

These results show that PCMs have good potential for heat retention inside the studied hybrid PCM/EG panel and could thus play a major role in increasing the efficiency of an ICS system. Furthermore, it could also address issues faced by the conventional ICS system. Further research in this topic is needed and it should focus on the ways of further increasing the thermal capacity of PCM/EG energy storage e.g. through increasing the amount of PCMs inside the collector. Future work on the system should also involve optimizing the system with phase change materials at higher melting points. The system should also be tested under various types of outdoors climatic conditions.

6. Acknowledgments

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7. References

Alzoubi, M. 2015. Modeling of compression curves of phase change graphite composites using Maxwell and Kelvin models. Journal of Composite Materials, 1–13. https://doi.org/10.1177/0021998315588624

Dabiri, S. 2016. Introduction of solar collectors and energy and exergy analysis of a heliostat plant.

Dincer Ibrahim, & Rosen A. Marc. 2011. Thermal energy storage systems and applications (Wiley John and sons, Ed.; Second).

Kessentini, H., Capdevila, R., Castro, J., & Oliva, A. 2011. Numerical and Experimental Study of a Flat Plate Solar Collector with Transparent Insulation and Overheating Protection System. https://doi.org/10.18086/swc.2011.19.20

Li, C., Zhang, B., Xie, B., Zhao, X., Chen, J., Chen, Z., & Long, Y. 2019. Stearic acid/expanded graphite as a composite phase change thermal energy storage material for tankless solar water heater. Sustainable Cities and Society, 44, 458–464. https://doi.org/https://doi.org/10.1016/j.scs.2018.10.041

Shi, T., Wei, S., & Yulan, Y. 2015. Characterization of Expanded Graphite Microstructure and Fabrication of Composite Phase-Change Material for Energy Storage. Journal of Materials in Civil Engineering, 27, 4014156. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001089

Whiffen, T. R., & Riffat, S. 2013. A review of PCM technology for thermal energy storage in the built environment: Part I. International Journal of Low-Carbon Technologies, 8, 147–158.

Zhang, Z., & Fang, X. 2006. Study on paraffin/expanded graphite composite phase change thermal energy storage material. Energy Conversion and Management, 47(3), 303–310. https://doi.org/https://doi.org/10.1016/j.enconman.2005.03.004