Journal Of Contemporary Urban Affairs

2017, Volume 1, Number 3, pages 7– 12

Experimental analysis of a flat plate solar collector with integrated latent heat thermal storage

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ARTICLEINFO:

Article history:

Received 2 August 2017

Accepted 10 August 2017

Available online 12 October 2017

Keywords:

Solar collector;

Thermal storage;

Latent heat storage.

ABSTRACT

In the present paper, an experimental analysis of a solar water heating collector with an integrated latent heat storage unit is presented. With the purpose to determine the performance of a device on a lab scale, but with commercial features, a flat plate solar collector with phase change material (PCM) containers under the absorber plate was constructed and tested. PCM used was a commercial semi-refined light paraffin with a melting point of 60°C. Tests were carried out in outdoor conditions from October 2016 to March 2017 starting at 7:00 AM until the collector does not transfer heat to the water after sunset. Performance variables as water inlet temperature, outlet temperature, mass flow and solar radiation were measured in order to determine a useful heat and the collector efficiency. Furthermore, operating temperatures of the glass cover, air gap, absorber plate, and PCM containers are presented. Other external variables as ambient temperature, humidity and wind speed were measured with a weather station located next to the collector. The developed prototype reached an average thermal efficiency of 24.11% and a maximum outlet temperature of 50°C. Results indicate that the absorber plate reached the PCM melting point in few cases, this suggests that the use of a PCM with a lower melting point could be a potential strategy to increase thermal storage. A thermal analysis and conclusions of the device performance are discussed.

JOURNAL OF CONTEMPORARY URBAN AFFAIRS (2017) ***1***(3), 7-12.

https://doi.org/10.25034/ijcua.2018.36zd72

www.ijcua.com

1. Introduction

Solar energy is the most widely available energy source in the world. However, it presents some obstacles to its implementation such as sensitivity to climatic conditions and intermittency. Therefore, it is necessary to develop technologies that allow storing solar energy for the periods in which it is not available, or its power is low. Two common methods of storing solar thermal energy are sensible and latent heat storage. While sensible heat is more common in practical applications, latent heat storage provides higher storage density, with narrow temperature variation. (Abhat, 1983) reported one of the earliest reviews on latent heat thermal storage. (Zalba *et al.*, 2003) reviewed thermal

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energy storage with PCM and its heat transfer analysis and applications. (Farid *et al.*, 2004; Kenisarin and Mahkamov, 2007; Nkwetta and Haghighat, 2014; Sharma *et al.,* 2009) reviewed solar energy storage using phase change materials. (Chandel and Agarwal, 2017) Reviewed the current state of research on energy storage, toxicity, health hazards and commercialization of phase changing materials. (Pandey and Chaurasiya, 2017) reviewed the analysis and development of solar flat plate collectors.

Although numerous works on latent heat storage, no commercial solar heaters with built-in PCM storage have been reported. However, preliminary studies in laboratory prototypes have shown considerable increases in efficiency and supply capacity. (Kürklü *et al.,* 2002) found a large difference between ambient temperature and water temperature both at day and at night. With the experimental techniques used, it was not possible to determine the phase change point at least in a general approach. No performance comparison is made against traditional devices. However they showed that its prototype has advantages in manufacturing cost and total weight for commercial devices, although it does not include an energy analysis. In countries with tropical climates, no scientific references have been found in studies of this kind of technology, in spite of the great capacity of available solar energy, quite possibly due to the lack of suitable commercial PCMs for this application. (Mehling *et al.,* 2003) presented experimental results and numerical simulation of a water tank with a PCM module using an explicit finite-difference method. Experiments and simulations indicated an increase in energy density of the tank of 20% to 45%. (Canbazoglu *et al*., 2005) Analyzed experimentally the time variations of the water temperatures at the midpoint of the heat storage tank of a solar heating system with sodium thiosulfate pentahydrate as PCM. It was obtained an increase in the produced hot water mass and total heat accumulated approximately 2.59–3.45 times of the conventional solar water-heating system. (Cabeza *et al.,* 2006) constructed an experimental solar pilot plant to test the PCM behavior in real conditions. It was obtained a discharge temperature stabilization near to 54 1C for a period of time between 10 and 12 h. (Mettawee and Assassa, 2006) performed parametric studies of different operating conditions, concluding that as the material melts, the heat transfer by convection increases the speed of the accumulation process. (Koca *et al.,* 2008) performed an analysis of energy and exergy a latent heat storage system with phase change material (PCM) for a flat-plate solar collector. The obtained experimental data showed that exergy efficiencies of latent heat storage systems with PCM are very low. However, the area of collector surface was smaller than that of the PCM surface area. As a result of this, the cost of the latent heat storage system was high and outlet temperature obtained was low. (Bouadila *et al.,* 2014) have developed an experimental study on a solar flat plate water heater with an accumulation of thermal energy in the collector using a PCM. Experimental measurements ascertain that the outlet temperature was not affected by the severe global solar radiation fluctuations. The solar collector remains a uniform useful heat around 400W during 5 h after sunset. (Serale *et al.,* 2014) present an approach to increase the performance of flat collectors based on the exploitation of the latent heat of the heat carrier fluid. The aim of this paper is to analyze experimentally the performance of a lab-scale solar collector built with commercial features and a latent heat storage unit inside it.

2. Method and materials

It was designed and constructed a flat plate solar collector prototype with a cavity to place macro-encapsulated PCM under the absorber plate. A schematic representation of the prototype is shown in Fig. 1. Further details of the collector are presented in Fig. 2 and described in Table 1.

The PCM was microencapsulated in 4 rectangular steel containers of 4000 X 4000 X 30 mm. Each container was filled with 3.35 kg of semi refined paraffin wax with a nominal melting point between 58-60 °C.

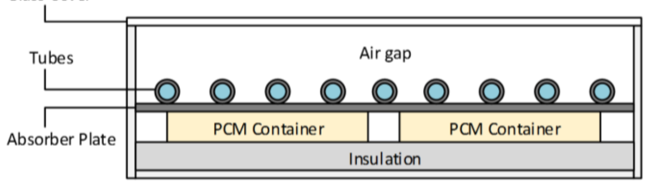

Figure 1. Schematic representation of the Solar Collector.

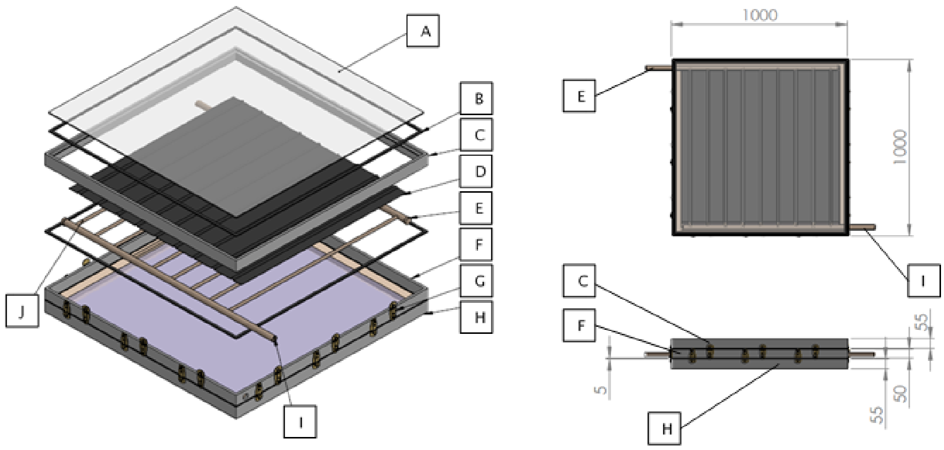

Figure. 1. Detailed view of the Solar Collector.

Table 1. Detailed component description of the collector

Item	Description	Specifications
A	Glass cover	Thickness: 4 mm
B	Gasket	--
C	Air cavity case	Thickness: 4 mm Aluminum
D	Absorber plate	Thickness: 1 mm Copper
E	Inlet line pipe	Diameter: 25.4 mm Copper
F	Plate Case	Thickness: 4 mm Aluminum
G	Lockers	--
H	PCM Cavity	Internal polyurethane insolation
I	Outlet line	Diameter: 25.4 mm Copper
J	Absorber pipes	Diameter: 12.7 mm Copper Separation: 100 mm

The experimental set-up is shown in **Error! Reference source not found.**. The water was supplied by an Aqua Pak LOOP 3V32-9/1115 pump with a fixed volumetric flow rate of 0.2 L/min and monitored by a rotameter Dwyer of 1.2 L/min. A weather station Davis Vantage Pro 2 Plus measured ambient temperature, wind speed, humidity and global solar radiation. Temperatures of the glass cover, confined air, absorber plate, water inlet, water outlet and PCM containers were measured with type-K thermocouples connected to a data acquisition unit Applent AT4532. 8 temperature channels were located on the absorber plate, 2 on the water inlet, 2 on the water outlet, 2 on the glass cover, 2 measured the confined air temperature, 4 on the top of the PCM containers and 4 at the bottom.

The experimental tests were carried out in 3 experimental campaigns with 20 days each one. The first campaign was performed in October 2016, the second in December 2016 and the third in February 2017. All at the test took place in Universidad del Norte campus, in Barranquilla Colombia (11°1'12.17"N,74°51'5.44"O). The test started at 7:00 AM monitoring all the variables every 5 minutes until the collector did not increase water temperature after sunset.

Figure 3. Experimental bank: 1. Water reservoir, 2. Pump, 3. Rotameter, 4. Solar collector, 5. Data acquisition unit, 6. Water reception tank, 7. Weather station.

3. Results & Discussion

Results of accumulated radiation, useful heat and efficiency during the 60 days of experimentation are presented in Figure 2 and summarized in Table 2. The highest efficiency of the collector was obtained in tests carried out in December while the lowest value during tests executed in October. As can be observed in Table 2, while low efficiencies are found both in rainy season with low radiation and clear season with high radiation the highest efficiency values were obtained during medium radiation values.

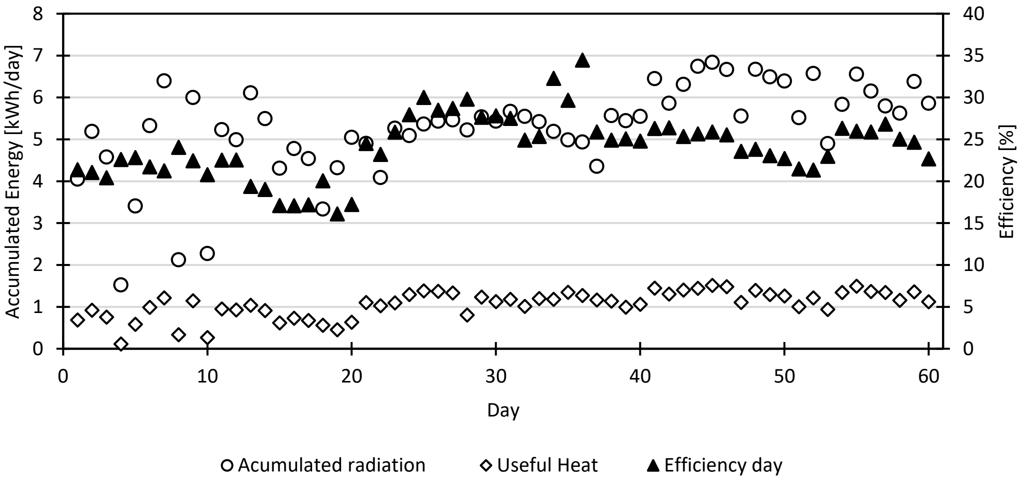

Figure 2. Experimental results by day.

Table 2. Results of the tests and weather conditions.

Exp. Campaign	Days in Figure X	Weather	Average Acc.rad [kWh/day]	Rad. Std. dev [kWh/day]	Average Efficiency [%]
Oct	01 - 20	Rainy	4.45	1.33	20.34
Dec	21 - 40	Scattered	5.22	0.41	27.44
Feb	41- 60	Clear	6.16	0.51	24.57
Total		-	5.27	1.10	24.11

The following graphs present the behavior of the collector on March 12, 2017. Figure 3 and Figure 4 shows respectively the solar radiation and wind speed measured by the weather station. This day has a high incidence of solar radiation with an accumulated radiation of 5.27 kWh. Figure 5 shows that the outlet temperature did not decrease too much during the cloudiness events of 11:00 and 15:00 which shows that the thermal energy storage system provides stability to the water supply.

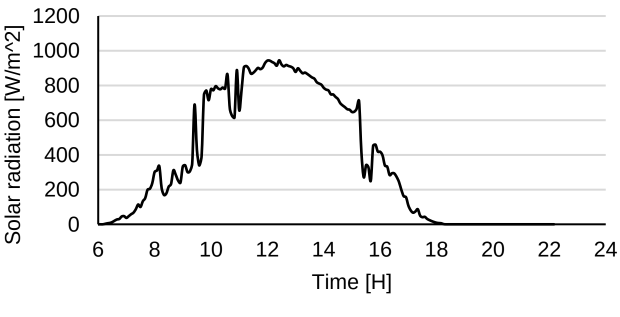

Figure 3. Solar radiation

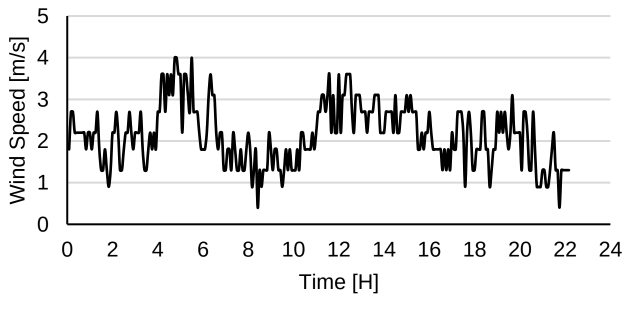

Figure 4. Wind speed

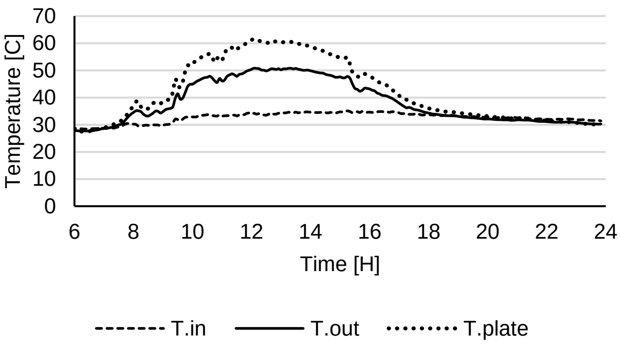

Figure 5. Temperatures of absorber plate, water inlet, and water outlet

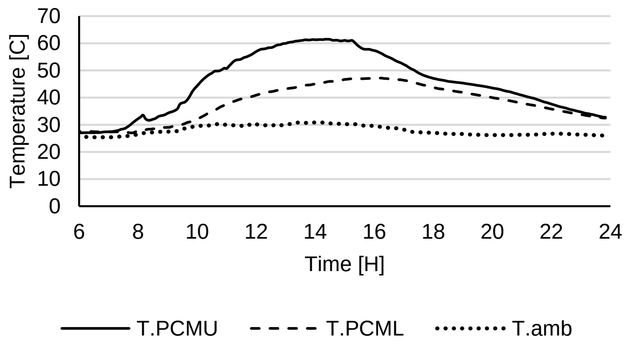

Figure 6. PCM Temperature and ambient temperature

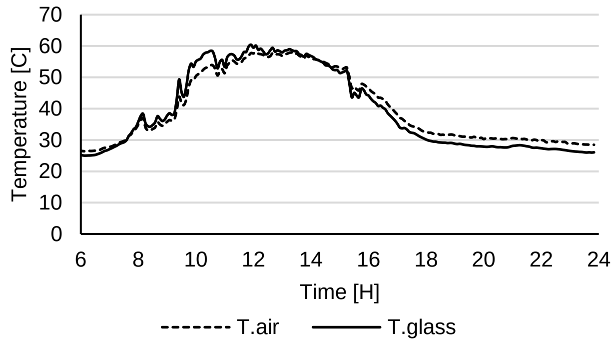

Figure 7. Temperature of air gap and glass cover

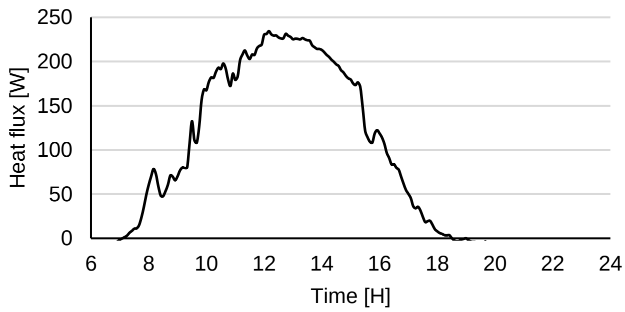

Figure 8. Useful Heat.

It can be observed in Figure 6 that the PCM containers store heat energy by sensible heat until 14:00, from where the temperature at container's top (T.PCMU) remains at 60°C until 16:00, indicating storage by latent heat. However, it should be noted in Figure 5 that the temperature of the absorber plate reaches the melting point of the PCM only for 2 hours, in many experimental tests the phase change temperature is never reached. This gives a short time to the PCM to accumulate energy by latent heat resulting in a PCM discharging process at a non-constant temperature. On the other hand, it can be seen in Figure 6 an asymmetric charge/discharge process. Despite the proper charging process during the morning the storage system was unable to provide thermal energy to the working fluid after 18:00 as can be seen in Figure 8 This may be due to an excess of PCM in the solar collector. In fact, Figure 6 shows that, although the upper part of the PCM reaches the phase change temperature, the lower part never reaches it and even its maximum temperature is reached about 2 hours later. Therefore, it can be inferred that during the night the molten PCM transfers heat to the solid PCM layers instead of the working fluid.

4. Conclusions

In this paper, an experimental analysis was carried out to evaluate the performance of a flat plate solar collector with integrated microencapsulated PCM as latent heat storage system. The highest efficiency of the prototype was obtained at accumulated radiation of 5.22 kWh/day. Values above or below this amount of radiation resulted in lower efficiency values. Asymmetric PCM charge/discharge process was observed. Therefore, reduce the PCM mass is recommended to avoid upper layers discharge thermal energy to lower layers instead of the absorber plate. It was obtained that the PCM modules provided stability to the outlet temperature against strong fluctuations in solar radiation. However, it was unable to supply thermal energy to the working fluid during the night. The short time the absorber plate reached the melting point of the PCM may be a cause of this. Thus, experimental analysis and simulation with PCM with lower phase change temperature is recommended.

Acknowledgments

This investigation has been partially funded by the Colombian Administrative Department of Science, Technology, and Innovation-COLCIENCIAS, through the program "es Tiempo

de Volver". Authors wish to express their acknowledgments to COLCIENCIAS and its excellent program.

Acknowledgement
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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