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EXPERIMENTAL ANALYSIS OF A SOLAR THERMAL ENERGY STORAGE SYSTEM BASED ON PHASE CHANGE MATERIALS (PCM) FOR AIR HEATING APPLICATIONS

Amaury José Oquendo Meza
Duban Andrés Villadiego Medrano
Jesús David Rhenals Julio
Arnold Rafael Martínez Guarín
Jorge Mario Mendoza Fandiño

Department of Mechanical Engineering, University of Córdoba, Carrera 6 No. 77-305 Montería - Colombia. ZIP code 230002
e-mails: aoquendomeza@correo.unicordoba.edu.co; dvilladiegomedrano@correo.unicordoba.edu.co; jesusrhenalsj@correo.unicordoba.edu.co; arnoldrafael@correo.unicordoba.edu.co; jorge.mendoza@correo.unicordoba.edu.co

Abstract. The use of available solar energy for domestic and industrial applications has been hindered due to its intermittent nature. In this context, several thermal energy storage (TES) systems have been implemented in solar radiation harvesting devices to mitigate this problem, to provide functional and efficient alternatives. These use sensible and latent heat to store heat in moments of high radiation and then release it in moments of low radiation, which are usually caused by cloudiness present in the areas where the task is carried out, so its implementation brings advantages such as a large capacity of heat storage in a small volume and an isothermal behavior during the loading and unloading processes of energy storage systems. Due to these advantages, in recent years, a lot of research work has been carried out to find more efficient phase change materials (PCM) and new system configurations to overcome the problems of low heat transfer between fluid working and phase change material (PCM). The present research aims to experimentally evaluate the impact of the implementation of phase change materials in flat plate solar collectors in the temperature and solar radiation conditions of the department of Córdoba in Colombia, specifically in the city of Monteria, to compare the thermal efficiency between them in transient operation. The parameters that affect the thermal performance of the flat plate solar air heater will be presented with phase change material and without phase change material. These parameters include solar radiation, air temperature difference across the heater, and instantaneous thermal efficiency. With this work, it is expected that the thermal energy storage system that has the phase change material (PCM) will show higher thermal efficiency and also at times when there is little solar radiation to obtain constant temperatures across the collector, ensuring better operation and performance for domestic and industrial applications.

Keywords: Thermal Energy Storage, latent heat, sensible heat, Phase Change Material, flat solar collector, Thermal Efficiency

1. INTRODUCTION

The lack of clean energies has motivated the scientific community in the world to look for alternatives to replace fossil fuels, due to their continuous scarcity, as a result of their massive consumption and polluting effect on the environment. Through research, it has been noted the great potential of solar energy as an alternative source, from which multiple technological and innovative systems have been developed (Sharma, et al, 2009). These technologies are environmentally friendly, and their use as a replacement for conventional energy sources helps to reduce emissions into the atmosphere causing the greenhouse effect that contributes to the deterioration of the atmosphere (Ingle, et al, 2013).

These systems are hampered by the intermittent nature of this form of energy, which can be mitigated by implementing thermal energy storage (TES) systems in solar energy harvesting devices. The main benefit of their

implementation is the large heat storage capacity in a small volume in sensible and latent heat mode, also an isothermal behavior during charging and discharging processes. Due to these advantages, a lot of research work has been done to find more efficient PCM and new configurations in the systems to overcome the problems of low heat transfer between the working fluid and the phase change material (Souliotis, et al, 2016). In some applications it is desirable to have low thermal conductivity, but this is often a problem when access to stored energy is required quickly (Zalba, et al, 2003).

Solar collectors have been implemented in different applications with transport fluids such as air and water. Their operation is involved in heating applications, with the use of solar radiation converted to thermal energy (Kürklü, et al, 2002). Researchers who have worked in this field, implemented various vessels in which they store the PCM indicated in their research, as an energy storage unit in the collector (Altobell, et al, 2011).

Flat plate solar collectors are widely used in drying applications in the area of food and grains, because they allow reaching temperatures around 100 °C (Victoria and Jaramillo (2005). Studies such as Torres-Gallo, et al, 2017, found that the collector efficiency was 43.91%, while the solar collector temperatures were maintained between 46 °C and 51 °C. This is due to a multitude of factors such as incident radiation and its intermittency, collector size, absorber plate size, its material type and configuration, among others. In another study, where water was used as transport fluid, it was found that the efficiency of the collector remained at values of 77.8% and 83.9% for simulation and experimental results, respectively. Similarly, the temperatures at the outlet had values of 30.89°C and 30.04°C (Garzón Romero and Ramírez Sapuy, 2015).

The objective of this research is to evaluate the thermal efficiency of two flat plate solar collectors in the city of Monteria, Cordoba, Colombia, where one of them contains a thermal energy storage system with the implementation of RT-45 kerosene as phase change material, in order to make comparisons between them and note the improvement provided by the storage system.

2. MATERIALS AND METHODS

2.1 Equipments

The solar collectors used in the experimentation had dimensions of 1 m long by 0.5 m wide, their walls were made of wood with a thickness of 15 mm and the perforations for air inlet and outlet had a diameter of 120 mm. To prevent heat loss from the absorber plate and the plates (0.9 mm galvanized sheets painted black) on each of the collector walls, 18 mm thick sheets of expanded polystyrene were installed. A 4 mm thick glass cover was applied to each of the collectors. Figure 1a shows the schematic of the collectors used, and one of them was fitted with a thermal energy storage system (TES) with RT-45 kerosene as shown in Figure 1b. This system consists of aluminum cans that were filled with PCM as storage unit and a staggered tube bank arrangement was made with intercalated rows of 4 and 3 cans, as shown in figure 2. The air inlet was provided by fans that delivered a speed of 5 m/s so that in the hot air outlet speeds of 4 m/s were obtained for the collector with TES and 4.6 m/s for the other one, these measurements were made with a Hold Peak vane anemometer, as shown in figure 3.
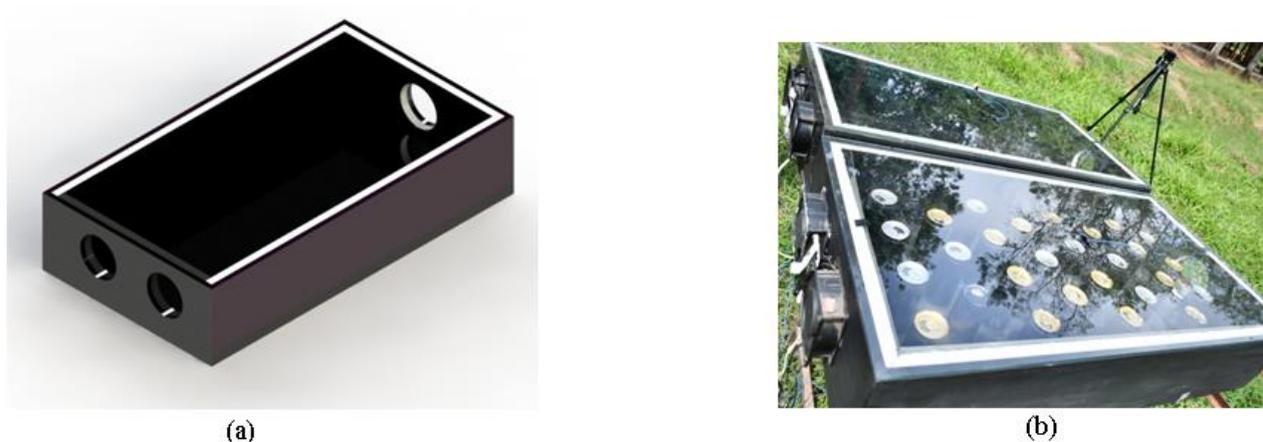

(a)

(b)

Figure 1. (a) Schematic of flat plate solar collector. (b) Flat plate solar collector with TES.

Solar radiation measurements were taken with a Davis Vantage Pro 2 weather station, which was positioned right next to the solar collectors, and its datalogger was configured to store the measurements in 1 min intervals. On the other hand, K-type thermocouples were used to take temperature measurements every second, using an Applent AT4208 data

acquisition device with 8 Channel, where the temperature was measured at the air inlet, at the absorber plate, at the surface of the thermal storage unit, at the air outlet and at the surface of the glass, with the purpose of calculating the thermal efficiency in each one of them.
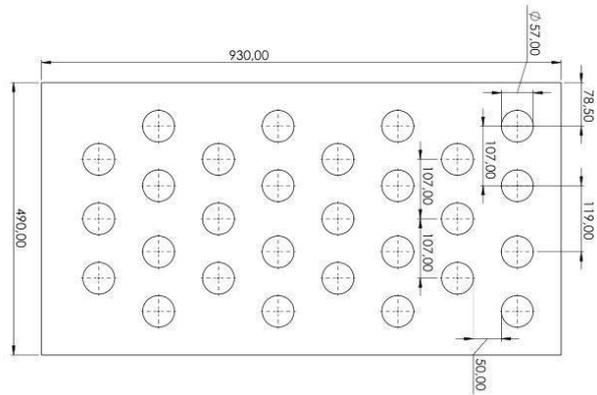

Figure 2. Can arrangement. (Dimensions in mm)

Figure 3. Measurements with an anemometer.

Figure 4. Davis Vantage Pro 2 weather station.

The experimental studies were carried out in March 2022 in the city of Monteria. Once the setup was installed, the measurements were performed in a space free of trees and buildings that could interfere with the measuring instruments present in the weather station, as well as cause shadows that would prevent the collection of solar radiation in the collector. In general, the experiments started between 8 and 9 a.m., when solar radiation began to be captured in the city, and ended around 5:30 p.m., when solar radiation values were very low and the ambient temperature dropped

considerably. From the data obtained, we took a day that represents the average day. With the results, we intend to calculate the instantaneous thermal efficiency of the collectors and then present the conclusions.

2.2 Efficiency of a flat plate solar collector

The efficiency of the solar collector is defined by the ratio between the useful energy gained in an infinitesimal time and the total energy incident on the collector in the same period.

$$\eta = \frac{\int Q_{useful}}{A \int I} \tag{1}$$

Where,

Q_{useful} , useful heat (W)

A , collector area (m^2)

I , incident radiation (W/m^2)

The incident radiation for our case study could be measured thanks to the weather station we used during the experiments, but we need to know the solar radiation for this we multiply the incident radiation by the collector area.

$$Q_{rad} = A \cdot I \tag{2}$$

Where,

Q_{rad} , solar radiation (W)

Now, to calculate the efficiency we need to know the Q_{useful} for which we have to take into account the inlet and outlet temperatures of the working fluid in the collector which was measured with thermocouples located at these points, we also need to know the mass flow and the specific heat of our working fluid.

$$Q_{useful} = \dot{m} C_p \left(T_2 - T_1 \right) \tag{3}$$

Where,

$\dot{m}$, air flow (kg/s)

T_1 , inlet temperature (K)

T_2 , outlet temperature (K)

C_p , specific heat $(kJ/kg \cdot K)$

3. RESULTS AND ANALYSIS

From the results obtained, the day on which the best results were obtained was taken and the experiment could be carried out throughout the day depending on the environmental conditions of the experiment. In order to carry out the analysis of the collectors, the experimental and operating conditions for the study day are presented, Figure 5 shows the incident radiation curves obtained from the weather station and the influence of the high cloudiness of this region of the country can be observed in the measurements made in the workplace.
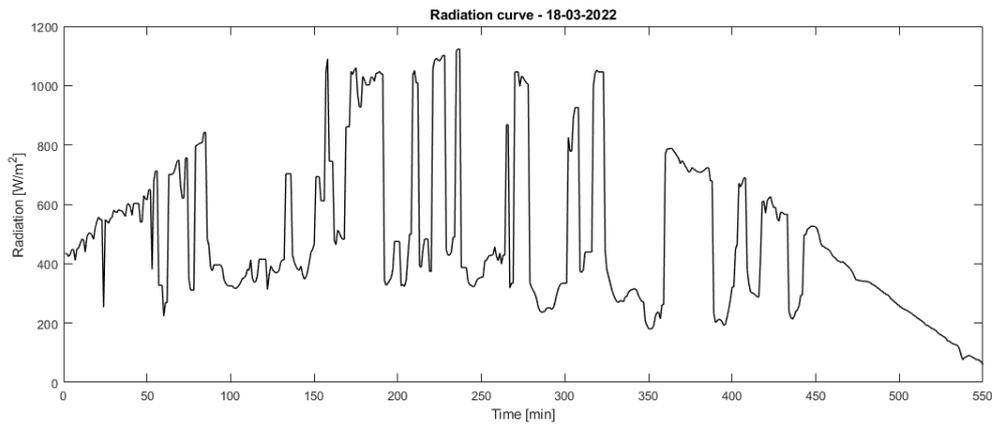
Figure 5. Radiation curve.

The temperature data obtained for the different solar collectors are presented below in a comparative way. It can be observed from the experimentation that the operating temperature of the absorber plate of the collector containing PCM is lower most of the time, but it is higher in the end part compared to the system without PCM, as shown in Figure 6.
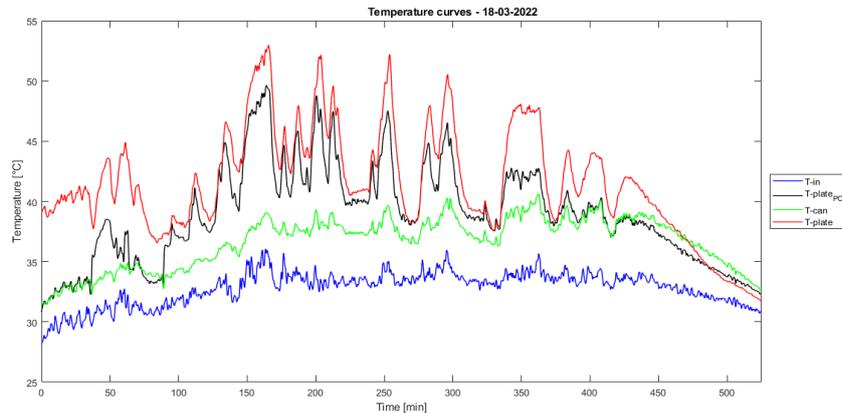

Figure 6. Experimental temperature of absorber plate with and without PCM and the can.

This behavior is due to the thermal energy storage of the phase change material during the hours of solar radiation and its functioning as a heat source during times of low radiation. It is also important to note that the effect produced by the shadow of the cans on the absorber plate prevents a smaller part of the plate from receiving solar radiation directly, which does not happen in the collector without PCM, which is directly exposed. Thus, the result of the inclusion of PCM in the temperatures of all system components, mainly in the absorber plate and the air outlet, which is consistent with the temperature curves in Figure 7, where the energy discharge of the storage units is presented and the temperature of the can is higher than the temperature of the absorber plate in the different collectors.
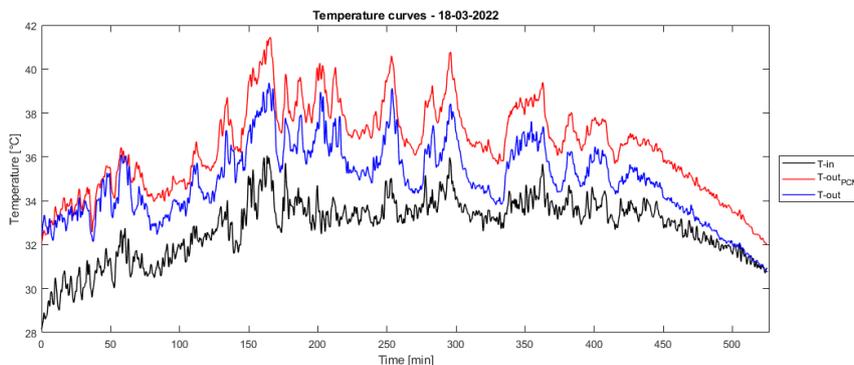

Figure 7. Experimental collector outlet and inlet air temperature with and without PCM.

In this order of ideas, Figure 6 shows that the output temperatures of the collectors are almost equal during the first hour of the experiment, as it progresses; it is observed how the collector with TES presents a better performance. Once

the afternoon hours arrive, there is a decrease in the inlet temperature, and the downward trend can be seen in the collector with traditional technology, while the collector with PCM makes use of the stored energy to have a better performance in its operating temperature. Figure 8 shows the temperatures measured on the surface of the glasses in the different collectors, which allows us to have an idea of the differences that can occur even in such a small work space under experimental conditions in the open air in uncontrolled environments, as well as the behavior of internal elements that can raise the temperature of the glass on occasions of low radiation.
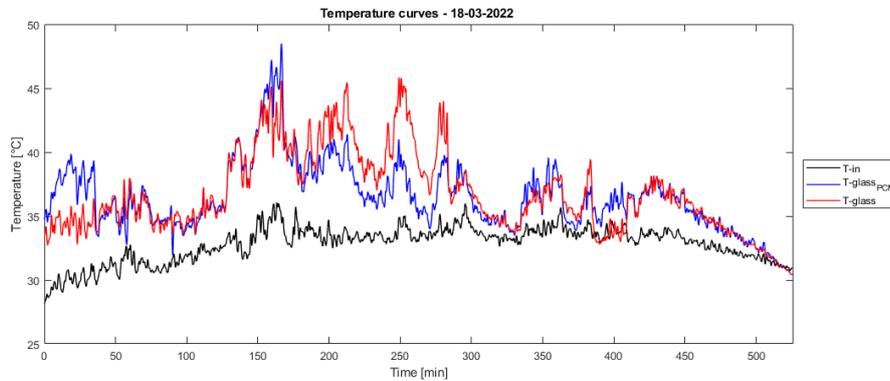

Figure 8. Experimental glass covers temperature with and without PCM

3.1 Efficiency of a flat plate solar collector

Regarding the calculation of thermal efficiency, Figure 9 shows the curve obtained for useful heat.
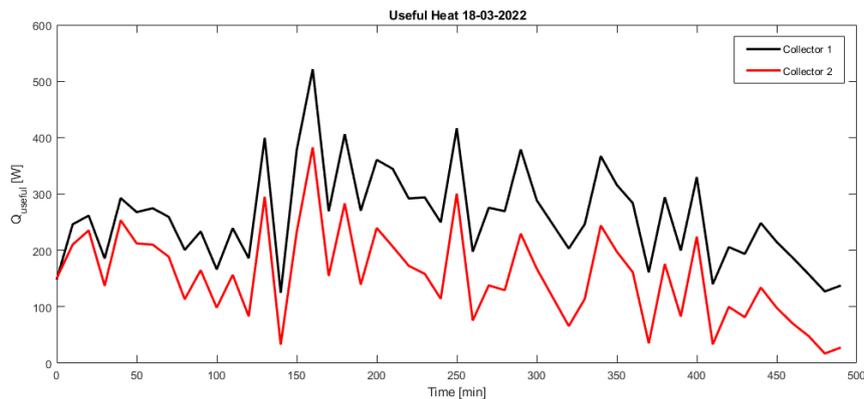

Figure 9. Useful heat for each solar collector.

The graph shows the similar behavior of both collectors as a consequence of the equality of the experimental conditions, being negligible small differences such as those presented in the glass temperatures in Figure 8. In this order of ideas, Figure 10 shows the instantaneous thermal efficiency every 10 minutes for both collectors, where the better performance of the collector with PCM can be seen, with a greater difference at the end of the day, when the solar radiation has decreased and the PCM begins to transfer heat to the surrounding air in forced convection. It should be noted that the instantaneous efficiency curve presents inconsistencies because at the end of the day the solar radiation presents very low values and the ambient temperature is equal to the outlet temperature, which means that the solar collector is not operating and gives an illogical result in the calculation of this efficiency, which does not occur for the solar collector with PCM, which continues operating, being the objective of this graph to compare the performance of both collectors at the end of the day when the heat stored in the PCM is discharged. Therefore, Figure 11 shows the thermal efficiency of both collectors during the day.
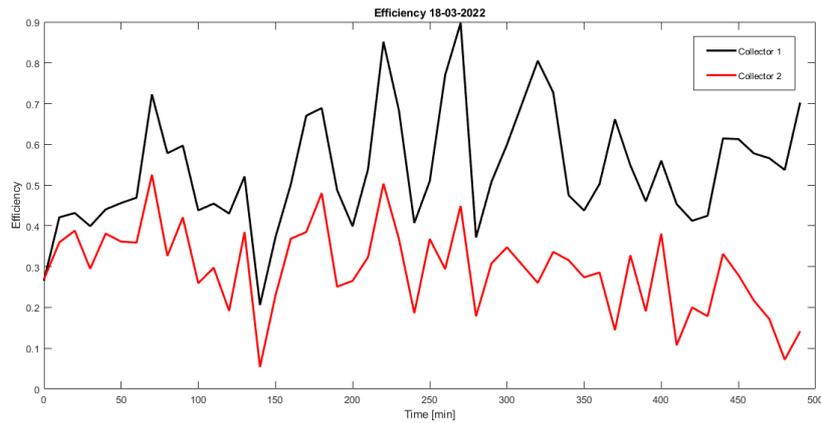
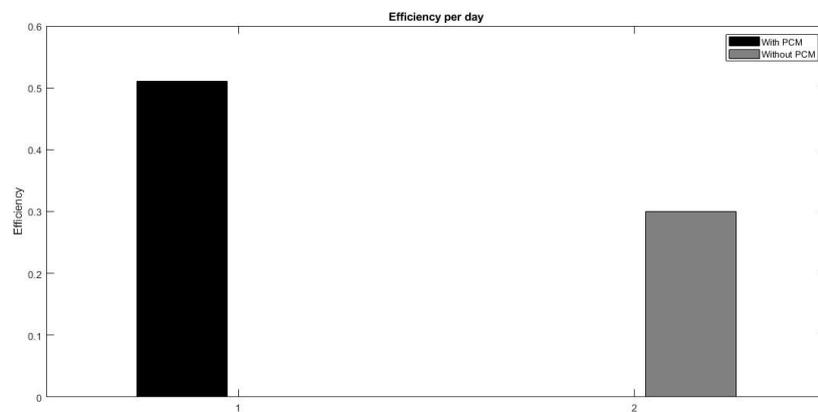Figure 10. Instantaneous thermal efficiency for each collector

Figure 11. Thermal efficiency of both collectors per day.

4. CONCLUSIONS

It was proven the great impact caused by the intermittency of this form of energy on the performance of the system. The PCM allowed the air heating process to continue at a higher temperature than that of the collector without the storage system when the solar radiation maintained a downward trend as shown by the results obtained. Although the absorber plate temperature of the collector without PCM maintained higher temperature values compared to the collector with PCM, the outlet temperature of the collector with PCM remained above the outlet temperature of the other collector during the whole experimentation. In the experimental process it was found that the thermal efficiency of the solar collector with PCM for the average experimental day was 51%, while the thermal efficiency of the collector without PCM had a value of 30% at an operating speed of $5 m/s$ at each inlet for the transport fluid.

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