Study the Effect of Phase Change Material on the Performance of Evacuated Tube Heat Pipe Solar Collector under Iraqi Climatic Conditions

Sarah H Ali¹, Adel A Eidan² and Assaad Al Sahlani¹

¹ Al-Furat Al-Awsat Technical University, Engineering Technical College of Al-Najaf, 31001, Iraq
² Al-Furat Al-Awsat Technical University, Najaf Technical Institute, Iraq

E-mail: alsahlan@msu.edu

Abstract. This work presents an experimental study to investigate the effect of integration phase change material (PCM) on thermal performance and efficiency of heat pipe-evacuated tube solar collector (HP-ETSC). The experiments were conducted under the Iraqi weather condition during the winter season (January, February, and March). To thoroughly investigate the thermal performance of HP-ETSC, a new experimental test rig was designed and manufactured based on standard criteria. The results showed that when integrating PCM with the system, it can significantly enhance the thermal capacity of the HP-ETSC system. The efficiency is increased by 3-5% and maintains the high temperature of water for a longer time at night. Moreover, the coefficients of evaporator heat transfer (EHTC) and condenser heat transfer (CHTC) of the heat pipe are also increased. The results from the developed HP-ETEC system are promising, and this experimental model can be applied using different types of phase change materials that are suitable to be used in Iraq.

Keywords. Phase change material, Tube heat pipe solar, PCM, HP-ETSC, PCM, EHTC.

1. Introduction

Solar energy is considered the most available source of renewable energy sources in the world [1]. The sun emits the heat energy to the earth, which forms 60% of its whole energy, and the rest of this energy is reflected and absorbed by the atmosphere. Solar energy is considered the basis of all known energy sources, such as wind energy, fossil fuels, etc. Solar energy can be transformed into electric energy and thermal energy; the electric energy is generated by photovoltaic, and a solar collector generates thermal energy. To obtain renewable energy, there are two problems: firstly, the high cost of production, and secondly, the low efficiency. The first problem can be solved by increasing the instruments which produce the desired energy. The second problem can be solved by using a large amount of solar energy that is available free of charge. The major problem of solar energy is not continuous during the days of the year, and this particular problem can be solved by using thermal storage. This energy can be stored during sunshine and used during sunset or its obliteration (eclipse). Thus, the energy can be available at any time during the year in order to fulfill all the essential needs during any time of the year according to the engineering designs [2-5]. The heat generated by the solar collectors from the sun radiation by the transfer medium can be used where there are two main kinds of collectors, which are the evacuated tube collector and the flat plate collector. It can be considered...
the main advantage for the evacuated tube solar collectors is relatively insensitive to the direction of sunlight. On the other hand, in flat plates, the situation is different where the direction of sunlight is significant. The other advantage of using the evacuated tube collector is the good insulation compared with the flat plate collector [6].

Ku¨rklu¨ et al. [7] presented a new kind of solar flat panel collector that contained two sections (adjoining), where the first one is filled with water and the second one with PCM. Canbazog¨lu et al. [8] studied the energy storage period for hot water. It was also investigated the amount of heat accumulated in the storage tanks of water that joined with phase change material (PCM). Cabeza et al. [9] built a new system of water heater, and it was added on the top of the tank of water PCM module in order to compensate for the amount of heat loss in the top layers. Also, it was studied the performance of the system of the water heater using a different number of PCM modules. Mettawee and Assassa [10] explored how to improve the thermal performance of the solar collector (flat panel) using PCM. It was used the unit of absorber plate container, where it has two tasks at the same time; the first task is absorbing the solar energy and, secondly, the medium of storage (PCM). Tarhan et al. [11] explored solar water heaters (built-in /three trapezoidal) using experimental investigation. It was investigated by the influence of the kinds of PCM and its location on the performance of the solar system (water heater). Browne et al. [12] studied, based on the experimental work, the performance of the thermal PCM system. A container made of stainless steel of a water pipe filled with PCM was used. Eidan et al. [13] utilized nanofluids to enhance the thermal performance of evacuated tube-solar collectors used for hot water applications. It was used a wide range of the filling ratios (between 40 to 80%) and tilt angles (between 30° to 60°) in order to find the optimal results. Also, Al Sahlan et al. [14-16] examined the effect of vibration on the performance of the thermal performance of the heat pipe- evacuated tube solar collector. A wide range of frequencies (from 2 to 10 Hz) was used to achieve the tasks of the research. It was found that the coefficients of the heat transfer for condensation and evaporation were increased dramatically under the vibration effect compared with the static condition. The main aim of this research paper is to experimentally study the effect of integrating phase change material (PCM) on the thermal performance and efficiency of heat pipe-evacuated tube solar collector (HP-ETSC). The focus here is to study the possibility of benefiting from hot water produced by the evacuated tube solar collector in the winter period and especially in the absence of solar radiation.

2. Experimental work

This section will provide full details about the built new test rig to achieve the required tests in this research. Two identical evacuated tube heat pipe-solar collectors were developed; the first one integrated with phase change material, and the second one is not integrated with phase change material. Both test rigs were operated together to study the effect of PCM on the thermal behavior of the developed system. It was tested the possibility of integrating the PCM with evacuated tube heat pipe-solar collector to enhance the thermal performance of the developed system under the Iraqi climatic conditions. Also, in the designed test rig, a measurement system is used to measure the temperature distribution at any time to study how will change the values of coefficients for the heat transfer (evaporation and condensation), and find out the thermal resistance of the system. Figure 1 illustrates the main parts of the new evacuated tube heat pipe-solar collector. As well, it can be seen in Figure 1, the schematic diagram that shows the setup outlines of the system with details.

All parameters and data used in the experiment test rig are listed in Table 1. Type K thermocouples were used during the experiments to measure the temperatures of the water tank and GA-HP and PCM. They were fixed in different levels and positions inside the system (HPET-SC) to find the amount of the internal content of energy accurately. Twenty-eight sensors probes were used to measure the temperatures; three sensors to measure the internal temperature of the evaporator; five sensors on the surface of the evaporation section; two sensors to measure the internal temperature of the condenser; and three sensors on the surface of the condensation section. Five sensors were utilized to measure the temperatures inside the water tank and five sensors in each tank of PCM. The data can be recorded during the boiling and condensation phenomena inside the gravity assist heat pipe (GAHP). The readings of the thermocouples during the experiments are recorded using a data logger.
The time interval for each reading is 5 s during the experiment. The capacity of the tank of water is equal to 5 liters, and the selected inclination angle for the solar collector is 45°. The experimental work was done in Najaf city, Iraq (latitude 31 °N and longitude 44 °E), during the winter months (January, February, and March). All the experiments were performed in sunny weather. A pyrometer is used to measure the global solar radiation instantly.

Based on the desired magnitude of the rate for water flow, the filling ratio is reached 70% of pure acetone, and the tilted angle is 45° under the ideal working conditions for the HPET-SC [17 & 18]. It was assumed that the HPET-SC system without PCM is the reference case study. It was used the paraffin wax as PCM, type RT42 in the present study, and the properties this material are listed in Table 2. The capacity of each tank of PCM is 1.8 kg. Generally, a summary of some essential points that were achieved for both cases are as follows:

1. Supply the heat pipe for both test rigs (with and without integrated PCM) with pure acetone at a filling ratio of 70% from the evaporator portion.
2. The daily period to conduct the experimental work is started from 8 am to 10 pm, and the temperatures were measured for the core and the surfaces at every 5 seconds.

In this study, it was made a calibration for each instrument used in the experimental work. These values represent the heat transfer coefficients for the evaporation and the condensation and the thermal resistance. The equation below is used to find the value of the overall thermal resistance for solar collector's \( R_{exp} \) as following [17, 18],

\[
R_{exp} = \frac{\bar{T}_E - \bar{T}_C}{2\pi r_o l_E}
\]  

Where;
\( \bar{T}_E, \bar{T}_C \): The average wall temperatures at the evaporator and condenser regions.
I (W/m²): Solar energy source which converts to the condenser from the GAHP evaporator and then dissipated by the water tank.
\( r_o \) (m): The external radius.
\( l_E \) (m): length of GAHP.

It can be calculated the heat transfer coefficients for the condensation section (CHTC) and evaporation section (EHTC) for both GAHP using the following equations,

\[
EHTC = \frac{1}{(\bar{T}_E - \bar{T}_o)}
\]  

\[
CHTC = \frac{l_E (l_E / l_C)}{(\bar{T}_o - \bar{T}_C)}
\]  

Where; \( l_E \) and \( l_C \) are the lengths (m) for the evaporator and the condenser. \( \bar{T}_o \) is the mean saturated temperature measured by core temperature sensors at the center of the GAHP.
Figure 1. (A and B) Setup and schematic diagram of the experimental rig for HPET-SC, (C) GA-HP thermocouple positions (surface wall and core).
Table 1. Details of HPET-SC’s design specifications. [17]

| Part             | Item                  | Specification                  |
|------------------|-----------------------|--------------------------------|
| Solar collector  | Type                  | Evacuated tube heat pipe       |
|                  | Collector area        | 0.06912 m²                     |
|                  | Material              | Copper                         |
|                  | Outer diameter        | 16 mm                          |
|                  | Inner diameter        | 14 mm                          |
| GA-HP            | Evaporator length     | 1150 mm                        |
|                  | Condenser length      | 200 mm                         |
|                  | Working fluid         | Pure Acetone                   |
|                  | Material              | Pyrex glass                    |
|                  | Length                | 1200 mm                        |
|                  | Outer diameter        | 50 mm                          |
| Glass envelope   | Inner diameter        | 45 mm                          |
|                  | Wall thickness        | 2.5 mm                         |
|                  | Vacuum                | 10-4 torr                      |
|                  | Transmittance         | 93 %                           |
| Flat reflector   | Material              | Aluminum sheet foil            |
|                  | Area                  | 1250×300 mm                    |
|                  | Material              | Aluminum 1 mm thickness        |
|                  | Capacity              | 5L                             |
|                  | Insulation            | 5mm Fiber Glass+3 mm           |
| Storage tank     | Outer shell           | Silicon+ Layer of Glass        |
|                  | A sheet of 3mm Alicabond |

Table 2. Properties of PCM paraffin wax.

| T_m °C | C_p kJ/kg K | k-solid W/m.K | k-liquid W/m.K | ρ-solid kg/m³ | ρ-liquid kg/m³ | H kJ/kg |
|--------|-------------|----------------|----------------|---------------|----------------|--------|
| 38-43  | 2           | 0.2            | 0.2            | 880           | 770            | 165    |

3. Results and discussions

It was performed the experimental tests in order to deeply study the thermal behavior of the evacuated tube heat pipe-solar collector under Iraqi climatic conditions. It was considered two different cases, the first one when integrating the phase change material and the second case without integrating the PCM. The tests were conducted in the winter season (January, February, and March).

Figure 2 shows the variation of water temperature in the storage tank for both cases (with and without PCM). It can be seen that there is no significant difference in the temperature for both cases until 5 pm (17:00). After that, it can be noticed the fast drop in the temperature for the without PCM case, while for the other case, the temperature is decreased very slowly. These temperatures will be useful for the whole day, especially when solar intensity is not available, where the lowest value of temperature is over 35 °C. The maximum temperature is approximately 54 °C for both cases at 4 pm (16:00).

Figure 3 shows the variation of thermal resistance with time for both cases. It can be noticed that the thermal resistance decreased when the increasing solar radiation time for both cases. The maximum values for both cases occurred at 8 am, and the minimum value occurred at 2 pm. It can be seen that the difference between the values of thermal resistance for both cases is minimal.

Figure 4 shows the variation of the evaporator heat transfer coefficient (EHTC) with time. It can be seen that both cases have the same behavior during the operation time and the difference between them is small and not exceed 70 W/m²°C. The maximum value of the EHTC occurs at time 12:00.

It can be considered that enhancement of the condensation process is an essential matter for all types of the heat pipe in order to increase the amount of transferred heat via convert the working fluid.
(vapor) into a liquid and then film back flowing to the section of evaporator via capillary effect or effect of gravity. Based on the available literature review, it was found that the most effective mode of heat transfer for the condensation is the dropwise mode. This mode provides rates for condensation higher than film-wise condensation \[18\]; it is commonly used in the industry sector, where it was made the surface like the non-wetting via the promoters. It may be coated with the long-chain fatty acids. Later on, the droplets will be formed and overgrows; the larger ones will be removed by gravity, and the process will be resumed. Experience showed that the most challenging task is to find the main characteristics of the non-wetting surface since removing the promoters by the liquid of condensed after a while.

Figure 5 shows the variation of condenser heat transfer coefficient with time for the same two cases (with and without PCM). Also, it can be seen that the behavior of both cases is similar during all time, but the values of the condenser heat transfer coefficient when using PCM is higher than those without PCM. The difference between them is not massive, and the maximum difference between them is not exceeding 100 W/m²K, where the maximum value of the CHTC occurred at time 12:00.

Figure 6 exhibits the efficiency of the ETHPSC system during the day of the experimental work for the same two cases (with and without PCM). It was selected as the most stable data from the total period of the experiment. It can be seen that the minimum value of efficiency appeared in the morning. The reason for such results is the minimum value for solar radiation that occurs in the early morning. In comparison, the maximum value of the efficiency occurs at noontime during the whole period for the experimental work, where the peak value of the solar radiation occurs at this time. This will lead to a fast increasing in the absorbed heat by the evaporator section compared with any other time during the experiment. Generally, the efficiency is increased when using the PCM, but the difference between the two cases is not exceeding 5 %.

Figure 2. The mean water temperature.
Figure 3. Variation of thermal resistance with time.

Figure 4. Variation of evaporator heat transfer coefficient with time.
4. Conclusions
In this research, a new experimental test rig was built to study the effect of phase change material (PCM) on the performance of evacuated tube heat pipe-solar collectors under the Iraqi climatic conditions. Generally, it was found that the thermal performance of the HP-ETSC system was enhanced when using PCM. The main point obtained is the possibility to keep the proper temperature (relatively hot) of water during the night time, where the temperature of the water was kept above 35
5. References

[1] Gordon J and Jeffrey M 2001 *ISES position papers* (Earthscan)
[2] Sukhatme P, and Nayak J 2017 Solar energy (McGraw-Hill Education)
[3] Sukhatme P, Nayak J 2008 *Principles of thermal collection and storage* (3rd Edition, Tata McGraw Hill Publishing company)
[4] Garg H 2015 *Solar energy: fundamentals and applications* (Tata McGraw-Hill Education)
[5] Mackay E, 2015 *Solar energy: An introduction* (OUP UK)
[6] Martin P, 2018 *Solar Collectors: Applications and Performance* (Nova Science Publishers)
[7] Kürkülü A, Özmerzi A, and Bilgin S 2002 *Renewable Energy* vol 26 no 3 p 391
[8] Canbazoğlu S, Şahinaslan A, Ekmekyapar A, Gökhan Y and Akarsu F 2005 *Energy and buildings* vol 37 no 3 p 235
[9] Cabeza F, Ibanez M, Sole C, Roca J and Nogues M 2006 *Solar Energy Materials and Solar Cells* vol 90 no 9 p 1273
[10] Eman-Bellah S and Assassa G, 2006 *Energy* vol 31 no 14 p 2958
[11] Sefa T, Sari A and Yardim M 2006 *Energy conversion and management* vol 47 no 15-16 p 2143
[12] Browne C, Lawlor K, Kelly A, Norton B and Cormack S 2015 *Energy Procedia* vol 70 p 163
[13] Eidan A, Al-Sahlani A, Ahmed A, Al-Fahham M and Jalil J 2018 *Solar Energy* vol 173 p 780
[14] Sahlani A and Eidan A 2018 (Journal of Mechanical Engineering Research and Developments) vol 41 no 3 p 67
[15] Ali S, Eidan A, Al-Sahlani A, Alshukri M and Ahmad A 2020 (Journal of Mechanical Engineering Research and Developments) vol 43 no 4 p 340
[16] Eidan, Adel A, Assaad Alsalhani and Kareem J Alwan 2017 *Experimental investigation on the performance of evacuated tube solar collector with wickless heat pipe under Iraqi climatic conditions* (Advances in Natural and Applied Sciences) vol 11 no 11 pp 11–19
[17] Eidan A, Al-Sahlani, A and Alwan K 2017 *AENSI* vol 11 no 11 p 11
[18] Hachim M, Alsahlani A and Eidan A 2017 *AENSI* vol 11 19 p 110
[19] Chopra K, Pathak A K, Tyagi V V, Pandey A K, Anand, S, Sari and A 2020 *Energy Conversion and Management* vol 203 p 112
[20] Kumar P M and Mylsamy K 2020 *Renewable Energ* vol 162 p 662
[21] Pawar, V R, Sobhansarbandi and S 2020 (Journal of Energy Storage) vol 30 p 101528
[22] Wang, Z, Yanhua D, Yaohua Z, Chuanqi C, Lin L and Tengyue W 2020 (Applied Energy) vol 261 p 114466