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Empirical Investigation of Thermal Features of Phase Change Material as Thermal Storage System

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ABSTRACT

This paper presents an empirical investigation of the melting processes of phase change material (PCM) in a tube and shell heating exchanger utilizing solar thermal energy. The experiments were conducted outdoors in Al-Mussaib city, Babylon, Iraq (Lat 32.5° North, long 44.3° East), utilizing a north-south (N-S) collector oriented at a tilt angle of 32.5° from the horizontal. This work utilized pure Iraqi black paraffin with 12 kg as PCM. The main empirical rig involves a vacuum tube solar collector (VTSC) utilizing a tube and shell heating exchanger to melt PCM in the shell regime. Different rates of water flow inside the internal heating exchanger's tube, namely (3.5, 5, and 8.5 L/m), were utilized for each season from August 2022 to January 2023. The empirical findings concluded that the internal tube inlet and surrounding temps significantly influence the melting process compared to the rates of water flow. It was found that the melting process of PCM needs about (3 to 4) hours in the summer season. Still, winter needs a longer time, about 14 to 16 hours. Increasing surrounding temp and solar radiation reduces the melting time of phase-change material. The findings of the present work were compared with the earlier investigations and agree with increasing the present work by 23.5 %. The findings from the present study are of practical importance for industries requiring storage materials to improve thermal storage system performance.

1. Introduction

Renewable energy from sun is the finally recognized explanation for the ever-escalating energy disaster. The use of clean and inexhaustible Renewable energy from sun is increasing rapidly. In many countries, direct solar radiation is considered an enormous energy that can be utilized in many industrial and economic fields. However, we need efficient storage materials and a great cost to extract an effective and large amount of Renewable energy from sun. Currently, energy sources are classified into three main parts: nuclear energy, fossil fuels, and renewable energy. The main cause of global warming for more than a century is radiation emissions and the use of fossil fuels, natural gas, and coal for energy generation. Most researchers are interested in finding alternative and renewable energy sources, although these sources are 40% of energy sources [1-3]. At present, the

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problems of energy transmission are at the forefront of thermo-physical research. The ongoing and swift advancement of technologies is paralleled by a perpetual escalation in the demands for the magnitude of heat flux densities being dissipated and enhancements in the safety and sustainable functioning of heat/mass transfer equipment [4,5]. We use Renewable energy from sun in our daily lives in several areas, such as steam generation, food keeping, refrigeration, heating, and electricity generation. Renewable energy from sun and its absorption methods and mechanisms that convert this energy into useful energy should be deeply studied to find the most appropriate and least expensive method [6,7]. Molten salts, mono and binary Nano-fluids, and PCM (Phase Change Materials) have been extensively deliberated by researchers as pivotal materials for Renewable energy from sun storage. These materials possess notable merits, including augmented heat storage capacity, reduced storage temp, isothermal operation, and minimized storage space requirements. Energy storage materials play a vital role in enhancing the efficiency of power generation processes, thereby contributing to energy preservation. Nevertheless, utilizing PCM for heat storage encounters several challenges stemming from its inherent characteristics, such as fluctuating thermo-physical features, limited thermal conductivity, phase segregation, sub-cooling, and incongruent melting [8,9].

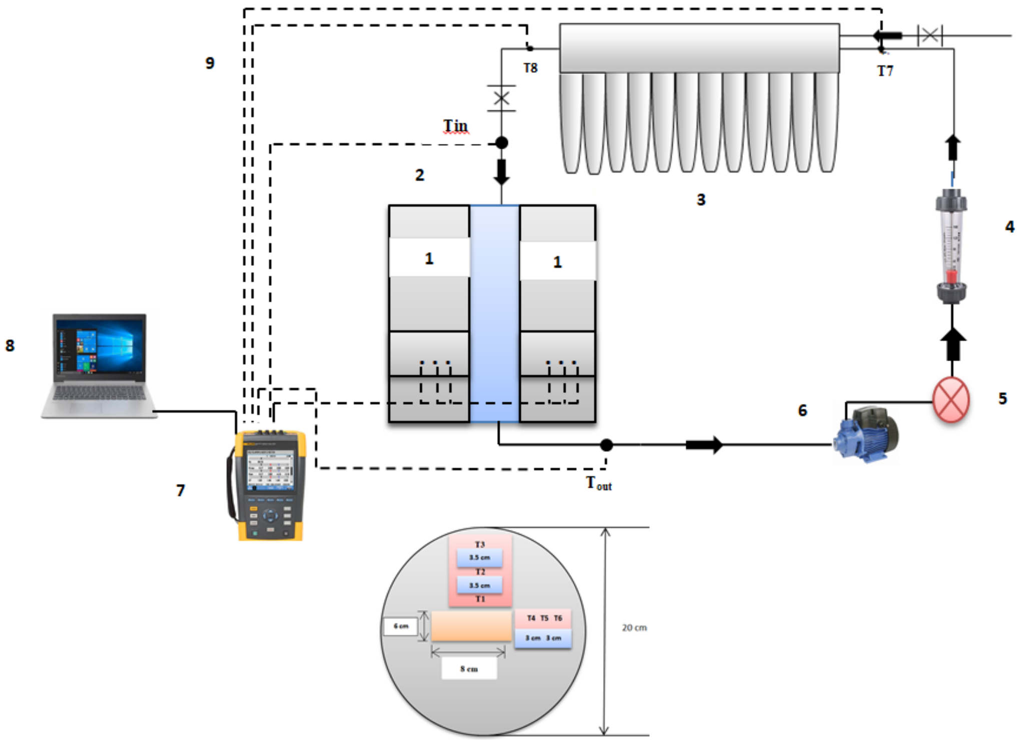
Heat is defined as a form of energy transferred between bodies with different temps, and it may be transmitted through the conduction, convection, or radiation processes [10]. The heating exchanger transfers energy between two liquids, which may be in direct contact or flow separately in two channels or tubes. In many industrial processes, there is a waste or dissipation of energy or a heat stream to the atmosphere, so heating exchangers are utilized to recover this heat and put it to use by heating various streams within the process [11,12]. Heating exchangers are typically equipped with surfaces that have been modified or corrugated to improve the transferring efficiency of heat mechanisms significantly. Corrugated or modified tubes serve as enhanced transferring of heat devices. They exhibit numerous advantages in engineering and practical applications due to their ability to promote secondary recirculation flow by generating non-axial velocity components [13,14].

Jesumathy *et al.,* [15] investigated the influences of circular Y-shaped fin arrangement to improve the low heat response rates of a double- heating exchanger's tube that incorporates PCM (Paraffin). Empirical and CFD) analysis were conducted to investigate the influences of circular Y-shaped fin arrangement on improving the low heat response rates of a double-heating exchanger's tube incorporating PCM (Paraffin). It has been determined that utilizing Y-shaped fins yields a reduction in the hardening duration of PCMs by approximately 22% while concurrently enhancing the discharging rate by approximately 26% compared to the implementation of straight fins. The empirical findings indicate a negative correlation between the duration of the hardening process and the fins' dimensions. Sinaringati *et al.,* [16] conducted an empirical investigation on applying beeswax and paraffin materials as heat energy sources for child incubators, with a subsequent comparison. The empirical findings demonstrated that implementing PCM within the confines of a child incubator chamber enables efficient thermal energy retention, sustaining a temp of 32°C or below for a duration exceeding eight hours. Beeswax exhibits superior energy storage capabilities compared to paraffin. It exhibits optimal performance once utilized as the PCM for a child incubator or any other practical application. Peng *et al.,* [17] investigated the utilization of low melt temp paraffin as a PCM in order to develop a series of thermal energy storage (TES) composites that integrate TES capabilities with structural functionality. The observed enhancement in thermal conductivity of the composites was attributed to the transition of the PCM into a liquid state, which can be attributed to two primary factors: firstly, the improved wetting of the epoxy matrix by the liquid paraffin, and secondly, the volumetric expansion of the paraffin liquid within the composite. Kenisarin and Mahkamov [18] studied the thermal features of various PCMs and their influence on the design of thermal storage systems and methods of improving transferring of heat. The following conclusions were reached by analysing the data in previous published research. Differential scanning calorimetry and differential thermal analysis techniques were the primary methods for investigating the thermal features of PCM and exhibit notable distinctions from rigorous thermo-physical methods. Keklikcioglu and Ozceyhan [19] investigated the thermal energy storage unit utilizing PCM. Utilizing latent heat thermal energy storage is a cost-effective solution that efficiently stores significant energy for continuous supply to the solar cavity receiver system, specifically designed with a helical coil configuration. In order to optimize the air conditioning functionality, materials with a melting temp below 15 degrees centigrade were meticulously chosen. In contrast, materials with a melting temp exceeding 90 degrees centigrade were judiciously employed for the absorption refrigeration system. All materials with melting points ranging from 15 degree centigrade to 90 degrees centigrade can be utilized in heat load levelling applications and solar heating. Mofijur *et al.,* [20] and Qi *et al.,* [21] empirically studied the thermal features of PCMs with many concentrations, methods of improving transferring of heat, and designing thermal storage devices for Renewable energy from sun systems, greenhouses, and solar cooking. Sharma and Chen [22] studied the influence of coiled wire and twisted tape inserts on transferring of heat enhancement methods. The flow type (laminar or turbulence) affects the thermodynamic performance in the heat exchange system. The findings revealed that utilizing twisted tape and coiled wire improved the transferring of heat rate and pressure drop or fluid friction. Prieto *et al.,* [23] illustrated the increasing thermal conductivity of PCM utilizing metal wool because the thermal conductivity of most PCMs was poor, reducing their commercial importance. The PCM should be impregnated in metal wool under vacuum conditions to ensure good thermal conductivity. It was illustrated that the metal wool does not present any physical or chemical degradation; this proves that the thermal conductivity improvement technique is suitable for this application. Srinivasaraonaik *et al.,* [24] studied the basics of PCMs, thermal features, and criteria for selecting PCMs that are commercially available. The focus has been on PCMs in solar water heating systems for buildings, especially in India, because 20–30% of electricity is utilized for hot water in households, institutional and residential buildings. The findings illustrated that flat plate collectors are more effective than vacuum tubes and concentrated collectors for warm water production at 55 to 70 °C household temps. Sikiru *et al.,* [25] illustrated a comprehensive review of developments of PCMs and their influence on the efficiency of solar storage systems. The authors explain how to improve the performance of photovoltaic systems by utilizing PCMs in these systems. Utilizing nanoparticles in conjunction with PCMs or transferring of heat fluid is a viable approach to augment the inadequate thermal conductivity of PCMs. In this regard, the dispersion of nanoparticles in a double-pipe heating exchanger was examined by Ali [26] to enhance the low thermal conductivity exhibited by the paraffin wax employed as a thermal storage medium. Rashid *et al.,* [27] and Harikrishnan and Kalaiselvam [28] studied the methods of storing Renewable energy from sun. Molten salts and Nano-fluids were utilized as storage materials for Renewable energy from sun. Different particles' absorption efficiency and influences were measured with changed concentrations, and the materials' thermo-physical and storage features were evaluated. The findings illustrated that adding Nano-materials to PCMs improves the efficiency of solar storage systems despite many obstacles to these materials, represented by the great cost, pressure drop, corrosion, and friction factor. The primary aim to evaluate the thermal characteristics of Phase change materials used for providing thermal energy experimentally under outdoor test for Iraq climate conditions.

2. Empirical Setup

2.1 Empirical Rig

The empirical setup comprises a vacuum tube solar collector (VTSC) that utilizes a tube and shell heating exchanger. The experiments were carried out to assess the influence of different environmental and collector water flow situations on the thermal performance of PCM. The empirical works were conducted at the Transferring of heat Lab of the Power Mechanics Engineering Faculty at Technical College Al-Mussaib (TCM), Al-Furat-Awsat Technical University (ATU), located in Kufa, Iraq. The experiments took place from August 2022 to June 2023. The location of the laboratory was at a height of 7 meters above the ground floor of a building. The geographical coordinates of the laboratory were latitude 32.5 º North and longitude 44.2 º East. The solar collector was oriented north-south and inclined at an angle of 32.5° concerning the horizontal plane. This tilt angle was chosen to maximize the absorption of incident solar radiation, which was particularly great at this angle. The empirical configuration employed for these tests featured a solar water collector. The collector is a vacuum tube design comprising a storage tank with a capacity of 100 litres and 12 evacuated tubes. It also includes a tube and shell heating exchanger, composed of a rectangular tube and a circular cylinder acting as the shell. The system comprises electric water pumps, flow meters, connecting pipes for component integration, glass wool insulators with a thickness of 15 mm to provide thermal insulation for the pipes, water valves, and a great safety valve system to prevent excessive pressure build-up at elevated water temps. Thermocouples, a computer, and a data logger are incorporated into the system, as depicted in Figure 1.



1-Pcm, 2-heating exchanger, 3-Evacuated tube solar collector, 4-Flowmeter, 5-Valve, 6- Pump, 7-Data logger, 8- Computer, and 9-Thermocouples

Fig. 1. Schematic diagram of the test rig

2.2 Instrumentation and Measurements

The measurement instruments employed in this endeavor consist of ten thermocouples of the K-type variety, capable of gauging temperatures within the range of 0 to 800 degrees Celsius. These thermocouples are strategically positioned throughout the empirical apparatus, as depicted in Figure 1. Each thermocouple is linked to a digital temperature reader, specifically a 12-channel temperature recorder, which exhibits an accuracy of ±3%. Flow control valves and a Nuritech flow meter, featuring a range of 2-15 l/m, are meticulously calibrated and installed within the flow lines to effectively regulate the rates of water flow. Additionally, a Lutran multifunctional anemometer apparatus, boasting a range of 0.4-30 m/s, is employed to precisely determine the velocity of the wind. A digital stopwatch and measuring container are used for calibration, while six thermocouples used by the process installation method are calibrated, as shown in Figure 2. Detailed information for the uncertainty analysis for this pilot study is given in Table 1. This is used to estimate measurement uncertainty for experimental data results.

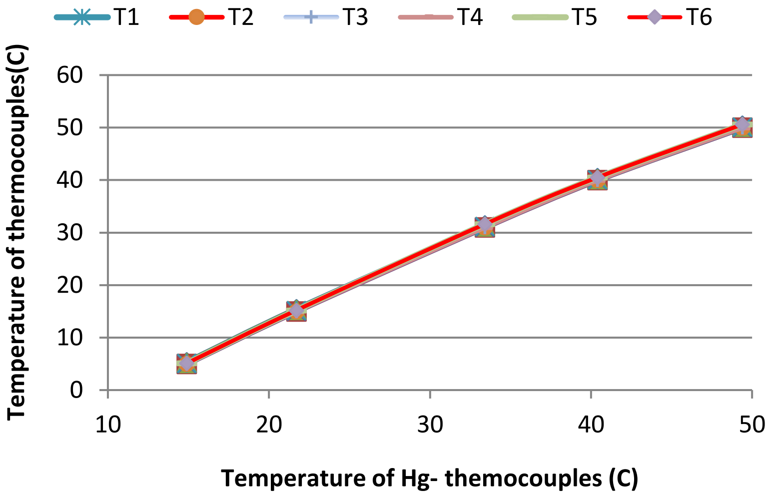


Fig. 2. Calibration cure of thermocouples

Table 1
The uncertainty analysis of the experimental work

Variables	Errors
T1	± 0.8
T2	± 0.8
T3	± 0.6
T4	± 0.6
T5	± 0.03
T6	± 0.03

2.3 Phase Change Materials (PCM)

For the empirical investigation, paraffin wax sourced from commercial suppliers was employed as the latent thermal energy storage material. Paraffin wax is a substance that exhibits non-toxic features and demonstrates chemical stability, thereby lacking regular decomposition. Additionally, it is capable of efficiently storing latent heat within a limited temp range. For the current experiment, a quantity of 12 kg of pure black paraffin sourced from Iraq was employed as the PCM. Table 2 presents the pertinent physical characteristics of PCMs.

Table 2
Physical features of paraffin PCM [29,30]

$C_{21}H_{44}$ Weight	12Kg
Density Solid/ liquid	912 kg/m^3, (769 kg/m^3)
Melting Temp	44 ± 0.5
Heating Capacity Solid/ liquid	2.4/2.0 KJ/Kg.k ± 3%
Thermal Conductivity Solid/ liquid	0.21/0.244 W/m.K
Fusion Heat	189 KJ/Kg
Specific heat	2.1 KJ/Kg.k
Viscosity	3.588 Pa.s

2.4 Empirical Facility

In the context of these empirical tests, Paraffin wax is employed as a medium for thermal energy storage within the shell heating exchanger system. The shell heating exchanger features an outer wall designed as a cylindrical structure, measuring 400 mm in height and 100 mm in radius. This outer wall is constructed utilizing aluminum material. On the other hand, the rectangular tube within the heating exchanger is fabricated from stainless steel and possesses cross-sectional dimensions of 60 mm by 80 mm. The liquefied paraffin was introduced into the shell heating exchanger. At the same time, the water was directed through the tube, creating a closed-loop system that facilitated circulation between the solar collector and the heating exchanger. Before commencing each empirical test, it is imperative to establish the precise time and date on the data recorder. Subsequently, establish a connection between the data recorder and all thermocouples, ensuring a comprehensive data acquisition system. At regular intervals of 30 minutes, the thermocouple data is systematically recorded and subsequently subjected to a meticulous auditing process. The intake valve pressurizes the water storage tank, and upon reaching the desired level, the valve is promptly shut to prevent further water flow. All empirical tests were recorded and organized in tabular format from the 1st of August 2022 to the 31st of January 2023, as specified in Table 3. Each test commenced at 0800 hours and concluded at 1700 hours post meridiem. Three rates of water flow were employed for each empirical test, specifically 3.5, 5, and 8.5 litres per minute (L/min). All experiments were carried out under varying meteorological conditions, encompassing partially obscured skies and unobstructed atmospheric conditions.

Table 3
The practical test dates and data

Flow rate l/m	Summer	Winter
3.5	6 August 2022	26-27 Jan 2023
5	8 August 2022	28-29 Jan 2023
8.5	10 August 2022	30-31 Jan 2023

The stages included in the empirical process are as follows:

Step 1: Raise the cover that protects the device from weather conditions such as dust and rain.
Step 2: Clean the glass cover of the solar water collector.
Step 3: Establish the interconnection between the thermocouples and the data loggers while ensuring proper alignment and secure fastening. Proceed to configure the date and time parameters of the data logger system. Data from all thermocouples were systematically recorded at regular intervals of 30 minutes and subsequently subjected to thorough scrutiny and verification.
Step 4: Open the intake valve and fill the storage tank with water.

Step 5: The intake valve is closed after the water flows out of the vent hole.
Step 6: Examine the device parts to ensure there is no water leakage.
Step 7: Make sure all valves are open in the rotation path.
Step 8: Pay attention to the global valve until the required flow is reached.
Step 9: Ensure that paraffin material is inserted into the container.

3. Thermal Performance Analysis

The thermal efficiency of the water solar collector defined as the ratio of heat gain (Q_u) supplied to area of aperture (A_a), and the solar radiation (I) which is incident on the area of aperture (A_a) [31]

$$\eta th = \frac{mcp(T0-Ti)}{IAa} \tag{1}$$

The thermal efficiency ηth of the water solar collector is calculated from the energy balance equation of the receiver. The useful energy as heat gain (Qu) transported to the receiver defined as [32]

$$Qu = (T_o - Ti) \tag{2}$$

where

Ti = inlet fluid temperature.
T_o = exit fluid temperature.

4. Results and Discussion

Empirical investigations are conducted to analyse the influence of various climatic and collector water flow conditions on the thermal characteristics of PCMs to gain a comprehensive understanding.

All empirical tests for PCMs were completed in the same summer semester, in August 2022; after that, all empirical tests conducted in the summer season were repeated in the winter semester, in January 2023.

Figure 3 and Figure 4 depict the correlation between the water inlet temps of the internal tube (Tin) and the temps of the PCM (T1, T2, T3, T4, T5, and T6) over hourly time intervals. These figures showcase the variations in temp for rates of water flow of 3.5 and 5 L/min on the 6th and 8th of August 2022, respectively, from multiple perspectives. The temp at which the water enters is greater than the max temp of the PCM. The rise in thermal energy resulting from solar radiation causes a corresponding increase in the temp of the inlet water and all temps of the PCM between 8:00 AM and 4:00 PM. The max temps of the PCM and the inlet water to the internal tube are recorded as 60.4 degree centigrade and 71 degree centigrade, respectively, once the flow water rate is 3.5 L/min. These temps are observed at 4:00 PM. Similarly, for a flow water rate of 5 L/min, the greatest temps are measured as 48.9 degree centigrade for the PCM and 67.1 degree centigrade for the inlet water at the same time. This temp variation is attributed to the differential radiation energy absorbed by the solar collector. Notably, the solar radiation intensity is greater for the 3.5 L/min flow water rate during the day of the experiment. The PCM undergoes melting at 12:00 for a flow water rate of 3.5 L/min and at 1:00 PM for a flow water rate of 5 L/min. This discrepancy in timing could be attributed to the greater storage thermal of the 3.5 L/min flow rate compared to the 5 L/min flow rate. Consequently, the melting point is reached after about 3-4 hours.

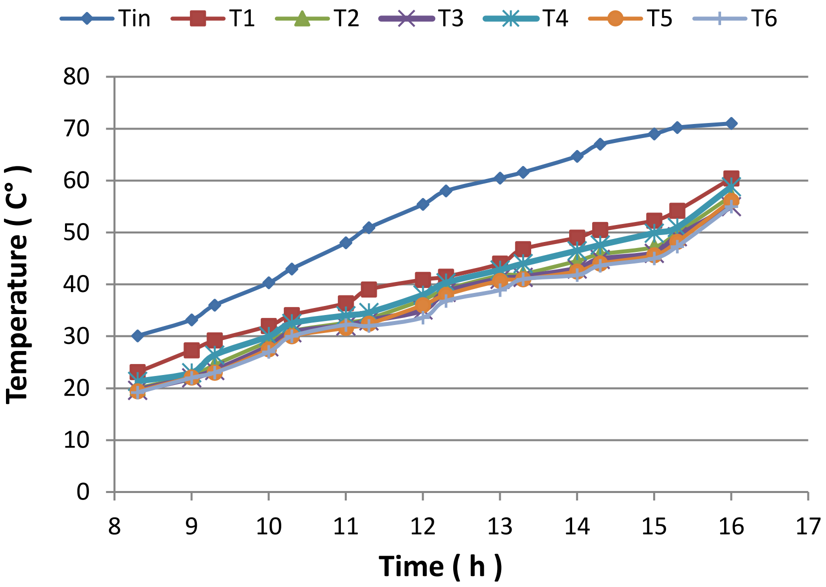


Fig. 3. Temps of PCM (3.5 l/m- 6th Aug 2022)

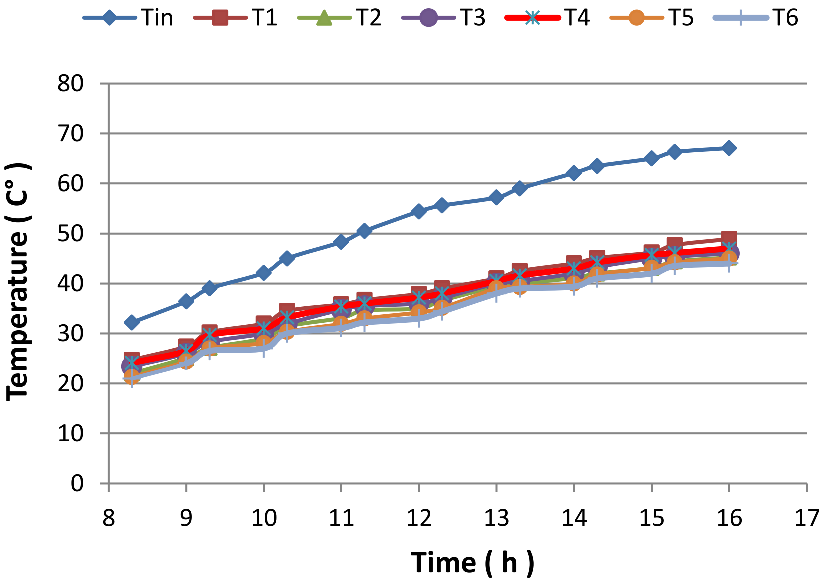


Fig. 4. Temps of PCM (5 l/m- 8th Aug 2022)

Figure 5 and 6 depict the correlation between the water inlet temps of the internal tube (Tin) and the PCM temps over hourly time intervals for a flow water rate of (3.5 L/min) on 6th August 2022, observed from various angles. Depends on the provided data, it is evident that T1 and T4 exhibit the greatest temps within the PCM, which could be attributed to their proximity to the surface of the internal tube, resulting in an enhanced transferring of heat rate compared to T2, T3, T5, and T6. Furthermore, it is evident that T1 exhibits greater temps than T4 due to the larger contact area of the PCM near T1 compared to T4. This asymmetry in the locations of the contact areas relative to the bulk temp of the water flow inside the rectangular internal tube further contributes to the temp disparity.

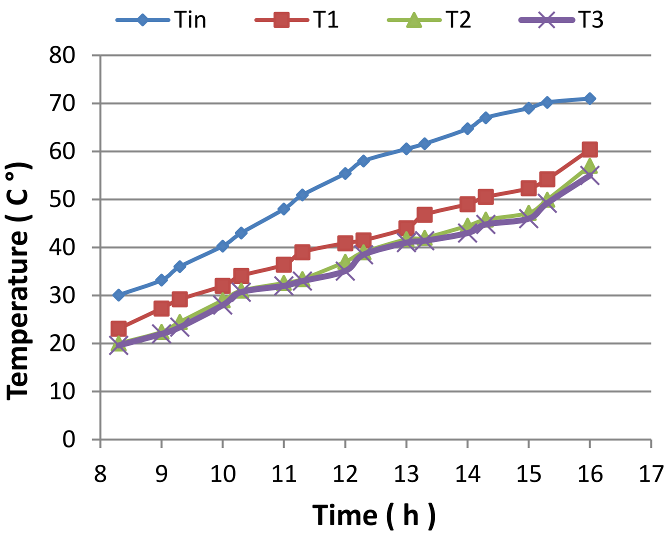


Fig. 5. (Tin, T1, T2, T3) (3.5 l/m- 6th Aug 2022)

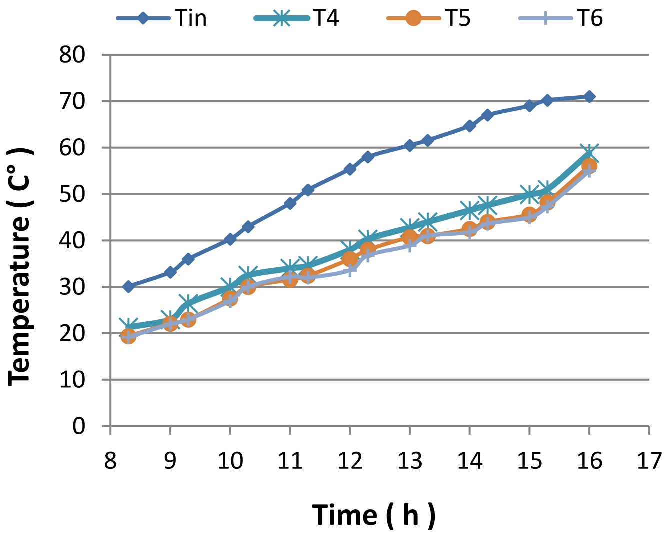


Fig. 6. (Tin, T4, T5, T6) (3.5 l/m- 6 th Aug 2022)

The relationship between inlet water temp (Tin) and middle temp of PCM (T2) with hourly time for rates of water flow of (3.5, 5, and 8.5 L/min in Aug 2022) are presented in Figure 7 and Figure 8, respectively. From Figure 7, the findings illustrated that the temp of the water entering the internal tube (Tin) for the flow water rate (8.5 L/min) is greater than the temp of the water entering the internal tube for the flow water rate (3.5, and 5 L/min) because the surrounding temp for the flow water rate (8.5 L/min) is greater than the surrounding temps for the rates of water flow (3.5, and 5 L/min), respectively. From Figure 8, It could be noticed that the middle temp (T2) of PCM for the flow water rate (8.5 L/min) are greatest temp than temps of the rates of water flow (3.5 and 5 L/min) due to the Renewable energy from sun and inlet temps for (8.5 L/min) flow water rate inside internal tube have greatest magnitudes than Renewable energy from sun and inlet temps of the rates of water flow (3.5, and 5 L/min), as presented in Figure 8.

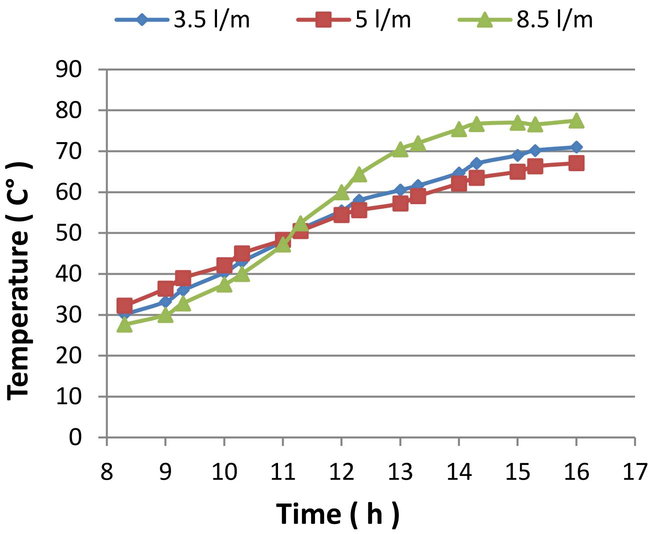


Fig. 7. Inlet water temp (Tin) in Aug 2022

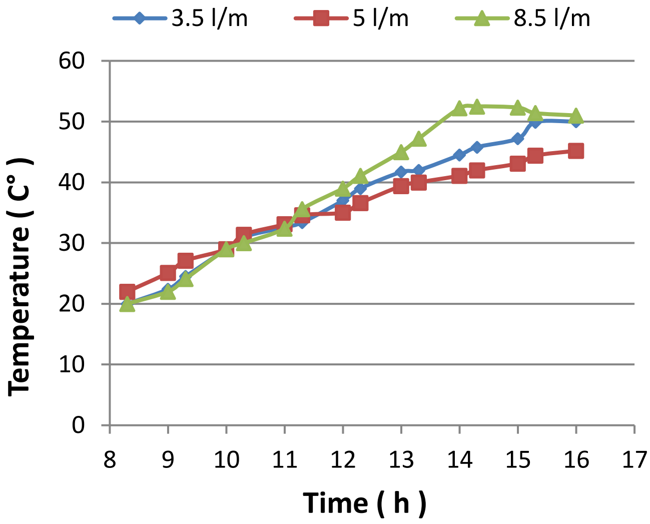


Fig. 8. PCM middle temp (T2) in Aug 2022

Figure 9 and 10 depict the correlation between the water inlet temps of the internal tube (Tin) and the temps of the PCM (T1, T2, T3, T4, T5, and T6) over hourly time intervals. The rates of water flow of 3.5 and 5 L/min are considered for two separate instances: the 26th and 27th of January 2023 and the 28th and 29th of January 2023. These relationships are presented from various angles to provide a comprehensive understanding. The detected water inlet temp exceeds the max temp of the PCM. The rise in thermal energy resulting from solar radiation causes a corresponding increase in the temp of the incoming water as well as all temps associated with the PCM during the period spanning from 8:00 a.m. to 11:30 p.m. The max temps of the PCM and the incoming water into the internal tube are recorded as 40.7 °C and 52 °C, respectively, once the flow water rate is 3.5 L/min. These temps are observed at 11:30 pm.

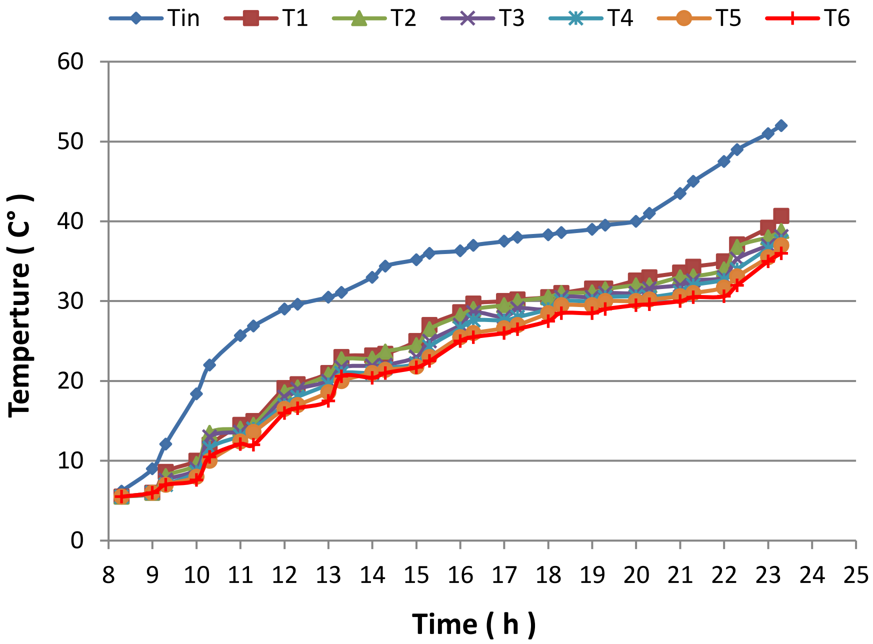


Fig. 9. Temps of PCM for (3.5 l/m on 26th and 27th Jan 2023)

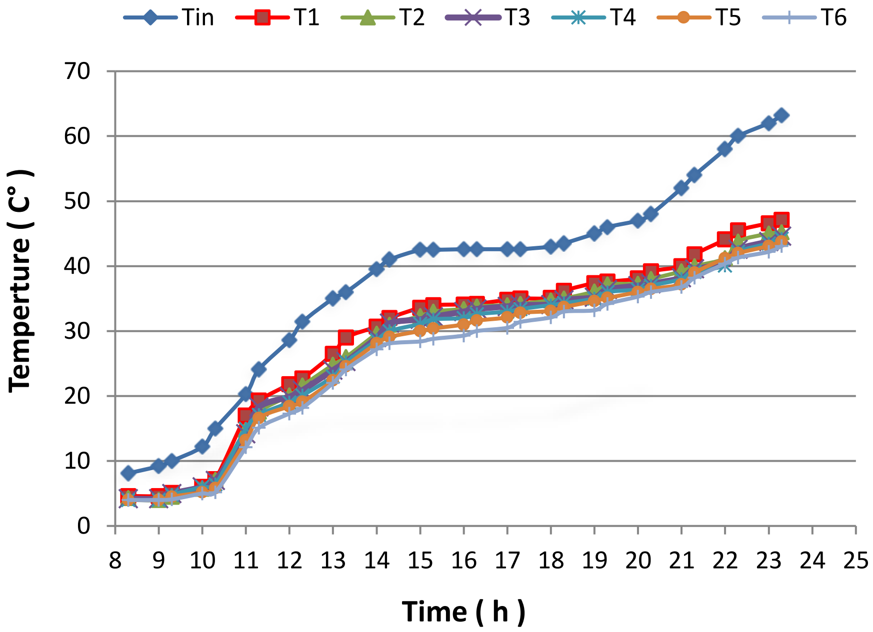


Fig. 10. Temps of PCM for (5 l/m on 28th and 29th Jan 2023)

Similarly, once the flow water rate is increased to 5 L/min, the greatest temps are measured as 47.1 °C and 63.2 °C simultaneously. The detected water inlet temp exceeds the max temp of the PCM. The rise in thermal energy resulting from solar radiation causes a corresponding increase in the temp of the incoming water and all temps of the PCM between 8:00 a.m. and 11:30 p.m. The max temps of the PCM and the incoming water into the internal tube are recorded as 40.7 °C and 52 °C, respectively, once the flow water rate is 3.5 L/min. This event takes place at 11:30 p.m.

Similarly, once the flow water rate is increased to 5 L/min, the corresponding temps are measured as 47.1 °C and 63.2 °C simultaneously. Depending on the empirical data, it could be deduced that the PCM undergoes a melting process that spans 16 hours once subjected to a flow water rate of 3.5

litres per minute. Similarly, once the flow water rate is increased to 5 litres per minute, the melting process occurs within a reduced period of 14 hours.

Figure 11 depicts the correlation between the water inlet temps of the internal tube (Tin) and the temps of the PCM (T1, T2, T3, T4, T5, and T6) over an hourly time interval. The data was obtained for a flow water rate of 8.5 L/min over a duration of two days, specifically on the 30th and 31st of January 2023. The measurements were taken from various perspectives to understand the system comprehensively. The detected temp of the water inlet exceeds the max temp of the PCM. Observation reveals that the inlet water temp and all temps of the PCM experience a rise over time, attributed to the augmentation of thermal energy resulting from solar radiation. The max temps of the PCM and the incoming water to the internal tube are recorded as 47.5 °C and 66 °C, respectively. These temps are observed at 11:30 p.m., maintaining a flow water rate of 8.5 L/min. The observation reveals that the phase transition, specifically melting, commences at 12:00 PM, precisely 16 hours into the process, with a volumetric flow rate of water set at 8.5 litres per minute.

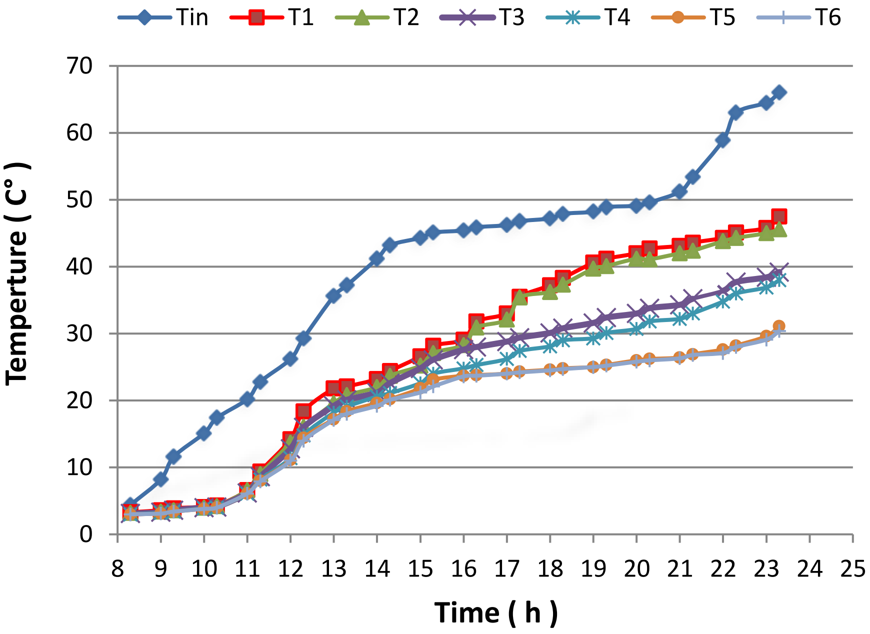


Fig. 11. Temps of PCM for (8.5 l/m on 30th and 31st Jan 2023)

Furthermore, depends on the analysis of Figure 9, Figure 10, and Figure 11, it is evident that T1 and T4 exhibit the greatest temps within the PCM system, which can be attributed to their proximity to the surface of the internal tube, resulting in enhanced transferring of heat rates compared to the other locations (T2, T3, T5, and T6). Furthermore, it is evident that T1 exhibits a greater temp than T4 due to the larger contact area of the PCM near T1 compared to T4. This asymmetrical distribution of the PCM's location relative to the bulk temp of the water flow within the rectangular internal tube further contributes to the temp disparity.

Figure 12 illustrates the relationship between inlet water temp (Tin) for PCM against hourly time for rates of water flow of (3.5, 5, and 8.5 L/min) in Jan. 2023. The findings detected that the temp of the water entering the internal tube (Tin) for the flow water rate (8.5 L/min) is greater than the temp of the water entering the internal tube for the rates of water flow (3.5 and 5 L/min), due to the surrounding temp for the flow water rate (8.5 L/min) are greater than the surrounding temps for the rates of water flow (3.5, and 5 L/min), respectively.

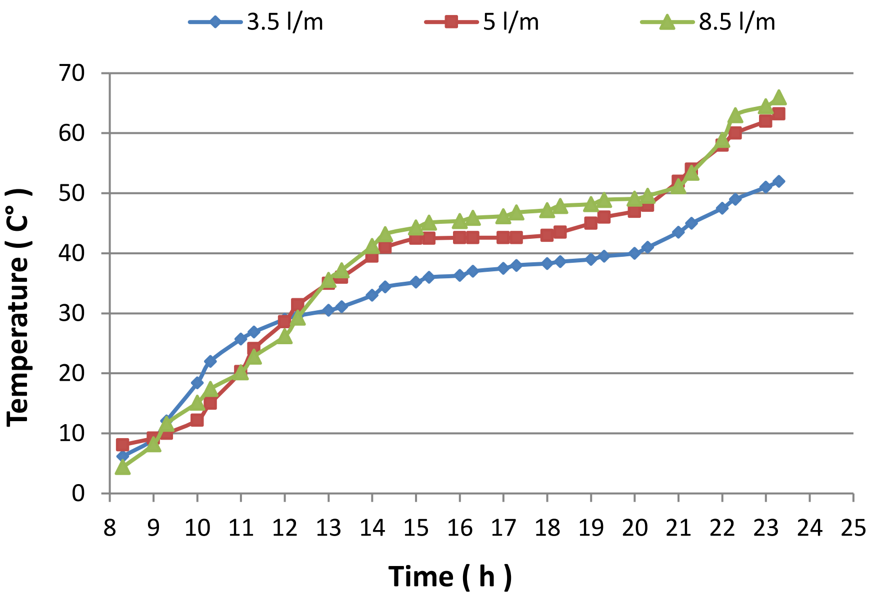


Fig. 12. Inlet water temp (Tin) on Jan 2023

The relationship among the middle temp of PCM (T2) against hourly time for rates of water flow of (3.5, 5, and 8.5 L/min) on Jan 2023 are presented in Figure 13. During the winter season, it takes two days for each flow rate to reach the melting point of the PCM. The middle temp (T2) of the PCM for the flow water rate of 8.5 L/min exhibits the greatest temps compared to the temps of the rates of water flow of 3.5 and 5 L/min, which can be attributed to the influence of Renewable energy from sun and the inlet temps for the 8.5 L/min flow water rate within the internal tube, which have greater magnitudes than the Renewable energy from sun and inlet the temps of the rates of water flow of 3.5 and 5 L/min, as depicted in Figure 11.

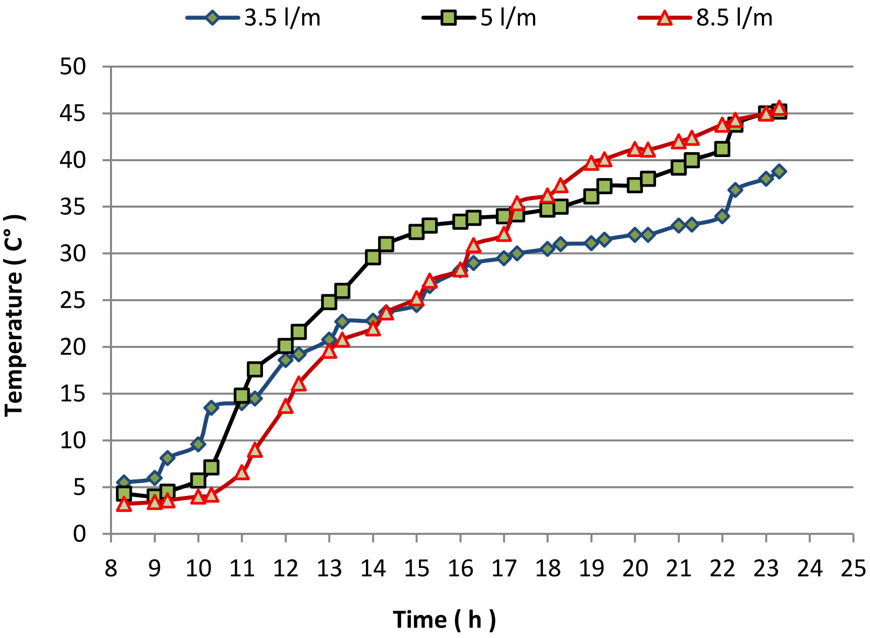


Fig. 13. PCM middle temp (T2) on Jan 2023

The findings from the current investigation are subjected to a comparative analysis with prior research endeavors. Figure 14 illustrates a comparative analysis of the middle temp of the PCM in the current study, in conjunction with a flow water rate of 3.5 litres per minute, in relation to the findings reported by Li [33]. The investigation pertains to the melting process under the influence of light radiation conditions within a laboratory setting. Depends on the depicted figure, it could be observed that the outcomes obtained from the current investigation exhibit a great level of concurrence with the findings of prior research endeavors.

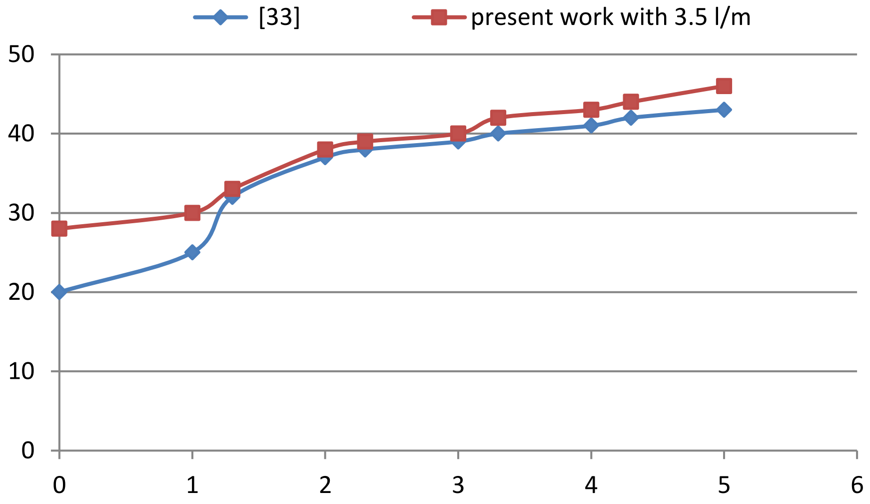


Fig. 14. Compares on between the present work and Li [33]

5. Conclusions

This investigation's comprehensive empirical analysis examines the melting phenomena of PCM within a tube and shell heating exchanger, employing solar thermal energy as the primary heat source. A quantity of 12 kg of pure Iraqi black paraffin was utilized for this study. The primary empirical setup comprises a vacuum tube solar collector (VTSC) employing a tube and shell heating exchanger to melt the shell region's PCM. A comprehensive analysis was conducted on various rates of water flow within the internal heating exchanger's tube. Additionally, an analysis was conducted to examine the influence of the tube's internal inlet and ambient temps. Depends on the empirical findings, it could be observed that the temp of the tube's internal inlet and the ambient temp play a crucial role in influencing the melting process of PCM as opposed to the rates of water flow. Upon analysing the temp distribution diagram of the PCM, it has been determined that the summer season necessitates approximately (3 to 4) hours for the melting process of PCM. However, during winter, it necessitates an extended duration of approximately 14 to 16 hours. Elevating the ambient temp and intensifying solar radiation decreases the duration necessary for the phase-change material to undergo melting.

References

[1] Dincer, Ibrahim. "Renewable energy and sustainable development: a crucial review." *Renewable and Sustainable Energy Reviews* 4, no. 2 (2000): 157-175. https://doi.org/10.1016/S1364-0321(99)00011-8

[2] Sheikholeslami, M., and M. Jafaryar. "Performance of energy storage unit equipped with vase-shaped fins including nanoparticle enhanced paraffin." *Journal of Energy Storage* 58 (2023): 106416. https://doi.org/10.1016/j.est.2022.106416

[3] Sheikholeslami, M., Z. Khalili, and S. J. Mousavi. "Influence of self-cleaning coating on performance of photovoltaic solar system utilizing mixture of phase change material and Graphene nanoparticle." *Journal of Building Engineering* 77 (2023): 107540. https://doi.org/10.1016/j.jobe.2023.107540

[4] Mhaske, G. B., and D. D. Palande. "Experimental and CFD analysis of tube in tubehelical coil heat exchanger." *International Journal of Engineering Research & Technology* 4, no. 8 (2015): 360-365. https://doi.org/10.17577/IJERTV4IS080441

[5] Kareem, Doaa, Hussein Al-Gburi, and Malik Hawas. "Investigate The Impact of Biodiesel Fuel Blends on The Characteristics of Engine and Releases of Single-Cylinder, Four Strokes." *Frontiers in Heat and Mass Transfer (FHMT)* 18 (2022). https://doi.org/10.5098/hmt.18.28

[6] Evans, Annette, Vladimir Strezov, and Tim J. Evans. "Assessment of sustainability indicators for renewable energy technologies." *Renewable and Sustainable Energy Reviews* 13, no. 5 (2009): 1082-1088. https://doi.org/10.1016/j.rser.2008.03.008

[7] Mekhilef, Saidur, Rahman Saidur, and Azadeh Safari. "A review on solar energy use in industries." *Renewable and Sustainable Energy Reviews* 15, no. 4 (2011): 1777-1790. https://doi.org/10.1016/j.rser.2010.12.018

[8] Shin, Donghyun, and Debjyoti Banerjee. "Enhanced thermal properties of SiO_2 nanocomposite for solar thermal energy storage applications." *International Journal of Heat and Mass Transfer* 84 (2015): 898-902. https://doi.org/10.1016/j.ijheatmasstransfer.2015.01.100

[9] Parsa, Seyed Masoud, Alireza Yazdani, Davoud Javadi, Masoud Afrand, Nader Karimi, and Hafiz Muhammad Ali. "Selecting efficient side of thermoelectric in pyramid-shape solar desalination units incorporated phase change material (PCM), nanoparticle, turbulator with battery storage powered by photovoltaic." *Journal of Energy Storage* 51 (2022): 104448. https://doi.org/10.1016/j.est.2022.104448

[10] Mohammed, Akeel, Hussein Al-Gburi, and Audai Al-Abbas. "Experimental Study of The Thermal Performance of Corrugated Helically Coiled Tube-In-Tube Heat Exchanger." *Frontiers in Heat and Mass Transfer (FHMT)* 20 (2023). https://doi.org/10.5098/hmt.20.17

[11] Jassim, Esam. "Spiral Coil Heat Exchanger-Empirical Study." In *Proceedings of the 3rd International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'16)*. 2016. https://doi.org/10.11159/ffhmt16.107

[12] Patil, A., and H. M. Dange. "Experimental studies of double pipe helical coil heat exchanger with micro fins." *International Journal for Innovative Research in Science & Technology* 1, no. 5 (2014): 33-37.

[13] Rainieri, Sara, and Giorgio Pagliarini. "Convective heat transfer to temperature dependent property fluids in the entry region of corrugated tubes." *International Journal of Heat and Mass Transfer* 45, no. 22 (2002): 4525-4536. https://doi.org/10.1016/S0017-9310(02)00156-4

[14] Abbas, Ali Sabri, and Ayad Ali Mohammed. "Enhancement Of Plate-Fin Heat Exchanger Performance with Aid of Various Types of Fin Configurations: A Review." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 99, no. 2 (2022): 48-66. https://doi.org/10.37934/arfmts.99.2.4866

[15] Jesumathy, S. P., M. Udayakumar, S. Suresh, and S. Jegadheeswaran. "An experimental study on heat transfer characteristics of paraffin wax in horizontal double pipe heat latent heat storage unit." *Journal of the Taiwan Institute of Chemical Engineers* 45, no. 4 (2014): 1298-1306. https://doi.org/10.1016/j.jtice.2014.03.007

[16] Sinaringati, Sekar, Nandy Putra, Muhammad Amin, and Fitri Afriyanti. "The utilization of paraffin and beeswax as heat energy storage in infant incubator." *ARPN Journal of Engineering and Applied Sciences* 11, no. 2 (2016): 800-804.

[17] Peng, Shuo, Alan Fuchs, and R. A. Wirtz. "Polymeric phase change composites for thermal energy storage." *Journal of Applied Polymer Science* 93, no. 3 (2004): 1240-1251. https://doi.org/10.1002/app.20578

[18] Kenisarin, Murat, and Khamid Mahkamov. "Solar energy storage using phase change materials." *Renewable and Sustainable Energy Reviews* 11, no. 9 (2007): 1913-1965. https://doi.org/10.1016/j.rser.2006.05.005

[19] Keklikcioglu, Orhan, and Veysel Ozceyhan. "A review of heat transfer enhancement methods using coiled wire and twisted tape inserts." *Heat Transfer-Models, Methods and Applications* (2018): Ch-10. https://doi.org/10.5772/intechopen.74516

[20] Mofijur, Mahlia, Teuku Meurah Indra Mahlia, Arridina Susan Silitonga, Hwai Chyuan Ong, Mahyar Silakhori, Muhammad Heikal Hasan, Nandy Putra, and SM Ashrafur Rahman. "Phase change materials (PCM) for solar energy usages and storage: An overview." *Energies* 12, no. 16 (2019): 3167. https://doi.org/10.3390/en12163167

[21] Qi, Qi, Yiqiang Jiang, and Shiming Deng. "A simulation study on solar energy seasonal storage by phase change material." In *2008 IEEE International Conference on Sustainable Energy Technologies*, pp. 106-109. IEEE, 2008. https://doi.org/10.1109/ICSET.2008.4746981

[22] Sharma, Atul, and C. R. Chen. "Solar water heating system with phase change materials." *International Review of Chemical Engineering (I. RE. CH. E.)* 1, no. 4 (2009): 297-307.

[23] Prieto, Cristina, Anton Lopez-Roman, Noelia Martínez, Josep M. Morera, and Luisa F. Cabeza. "Improvement of phase change materials (PCM) used for solar process heat applications." *Molecules* 26, no. 5 (2021): 1260. https://doi.org/10.3390/molecules26051260

[24] Srinivasaraonaik, Banavath, Shishir Sinha, and Lok Pratap Singh. "Phase Change Materials for Renewable Energy Storage Applications." In *Management and Applications of Energy Storage Devices*. IntechOpen, 2021. https://doi.org/10.5772/intechopen.98914

[25] Sikiru, Surajudeen, Temidayo Lekan Oladosu, Temitope Ibrahim Amosa, Sanusi Yekinni Kolawole, and Hassan Soleimani. "Recent advances and impact of phase change materials on solar energy: A comprehensive review." *Journal of Energy Storage* 53 (2022): 105200. https://doi.org/10.1016/j.est.2022.105200

[26] Ali, Hafiz Muhammad. "Phase change materials based thermal energy storage for solar energy systems." *Journal of Building Engineering* 56 (2022): 104731. https://doi.org/10.1016/j.jobe.2022.104731

[27] Rashid, Farhan Lafta, Mudhar A. Al-Obaidi, Anmar Dulaimi, Haitham Y. Bahlol, and Ala Hasan. "Recent Advances, Development, and Impact of Using Phase Change Materials as Thermal Energy Storage in Different Solar Energy Systems: A Review." *Designs* 7, no. 3 (2023): 66. https://doi.org/10.3390/designs7030066

[28] Harikrishnan, S., and S. Kalaiselvam. "Experimental investigation of solidification and melting characteristics of nanofluid as PCM for solar water heating systems." *International Journal of Emerging Technology and Advanced Engineering* 3 (2013): 628-635.

[29] Abhat, A. "Low temperature latent heat thermal energy storage: heat storage materials." *Solar Energy* 30, no. 4 (1983): 313-332. https://doi.org/10.1016/0038-092X(83)90186-X

[30] Wei, Huang. "An Overview On Properties And Classification Of Wax Phase Change Material (WPCM)." *European Chemical Bulletin* 1, no. 8 (2012): 305-306.

[31] Ma, Jinwei, Wei Sun, Jie Ji, Yang Zhang, Aifeng Zhang, and Wen Fan. "Experimental and theoretical study of the efficiency of a dual-function solar collector." *Applied Thermal Engineering* 31, no. 10 (2011): 1751-1756. https://doi.org/10.1016/j.applthermaleng.2011.02.019

[32] Abbas, Ali Sabri, and Ayad Ali Mohammed. "Improvement of Plate-Fin Heat Exchanger Performance with Assistance of Various Types of Vortex Generator." *CFD Letters* 15, no. 7 (2023): 131-147. https://doi.org/10.37934/cfdl.15.7.131147

[33] Li, Yongcai. "Thermal performance analysis of a PCM combined solar chimney system for natural ventilation and heating/cooling." *PhD diss., Coventry University*, 2013.