Thermal Storage by Parabolic Trough Solar Collector in Ouargla Region

Intissar Achouri[1], Mohammed Elbar Soudani[1], Djamel Bechki[1], Yacine Marif[1]

[1] Laboratory for Development of New and Renewable Energies in Arid and Saharan Zones (LENREZA)

University Kasdi Merbah Ouargla

Email corresponding author: achouri.intissar@univ-ouargla.dz

Received: 07/ 2023; Published: 08/ 2023

Abstract:
The Parabolic Trough Collector (PTC) is one of the most widely used collectors in industrial applications for water heating and hot steam production. Significant efforts have been made to improve its efficiency and effectiveness.
In this experimental work, (PTC) has been integrated with a thermal storage system. A theoretical and experimental study was conducted to test the performance and effectiveness of thermal energy storage using paraffin wax as a phase change material (PCM) for latent heat storage. The study was carried out from 07:00 AM to 03:00 PM, utilizing a tank coupled with the PTC system to compensate for interruptions during periods of no sunlight. The study demonstrated the efficiency and impact of paraffin wax on the operation of this solar system, particularly during the phase change stage in the charging phase.
The useful heat gain, solar energy collected per hour, and solar energy stored per hour by the solar collector were determined. The peak was observed at noon and was found to vary with changes in solar radiation. The amount of useful energy acquired by the fluid continues to increase after noon, reaching a maximum value of 5585.64 W due to the transfer of heat from the storage material to the fluid.
In contrast, in the absence of the storage material, the amount of useful energy reaches a maximum value at noon, estimated to be 864.70 W, and then decreases after noon due to heat losses. It was noted that the charging efficiency, when the storage material is present, initially reaches a maximum value of 82.96% and then decreases as solar energy is converted into useful heat for the fluid on one hand and stored heat in the storage material on the other.
In addition, a numerical model was developed using PTC and PCM, and the validity of this model was verified by comparing it with the experimental work.
Keywords: solar radiation, parabolic trough collector, thermal energy storage, phase change materials.

Tob Regul Sci. ™ 2023;9(1): 4085-4103
DOI: doi.org/10.18001/TRS.9.286

1- Introduction

Fossil fuels have experienced significant consumption over the past decade due to the increasing energy demand. This has had environmental impacts and contributed to global warming [1]. Therefore, it has become necessary to reduce the use of fossil fuels and, more importantly, preserve the lives of living organisms from the risks of environmental pollution by seeking new and renewable energy sources.

Solar energy is one of the largest, most abundant, and cost-effective forms of renewable energy in the world [2], [3]. It is considered one of the most important renewable energy sources and a promising option because it is clean and readily available. Solar energy has multiple applications in thermal systems, which have gained significant attention.

Concentrated Solar Power (CSP) relies on concentrating direct solar radiation to heat a fluid and generate electricity [4]. These technologies are effectively utilized in regions that receive high levels of direct solar radiation, as this process occurs in two stages. The first stage involves the absorption and concentration of solar energy, converting it into heat. The second stage involves converting this heat into electricity.

The availability of solar radiation throughout the day, a wide surface area, and the presence of a water source for cooling and cleaning the reflectors are essential for the development of these technologies. CSP plants are expected to witness significant advancements worldwide, including in North Africa, due to the aforementioned factors [5]. There are four types of CSP plants, which include solar parabolic dishes (SPD), parabolic trough collectors (PTC), solar power towers (SPT), and linear Fresnel reflectors (LFR).

The Parabolic Trough Collector (PTC) is considered one of the most important Concentrated Solar Power (CSP) systems used in industrial applications for producing hot water and steam [6]. The global contribution of PTC systems to power generation is approximately 73.58%, and it is expected to reach around 800 GW, thereby preventing the emission of 1.2 billion tons of CO_2 annually by the year 2050 [7][8].

The city of Ouargla is located in southeastern Algeria, at an elevation of 164 m. It is situated at a latitude of 31.57 °C North and a longitude of 5.21°C East [9]. It has a desert climate characterized by low temperatures in winter and extremely high temperatures in summer. Its geographical location and unique climate make it one of the regions known for abundant solar radiation. The average solar energy flux on a horizontal surface in the south (desert) reaches 2650 kWh/year/m^2 with approximately 3500 hours of sunshine per year [8].

However, the intermittent nature of solar radiation has led researchers and scientists to search for solutions to bridge the gap during periods of low or no sunlight. One of the most important options and available solutions is the development of Thermal Energy Storage (TES) technologies [3], which are equally important as developing new energy sources. TES systems offer the possibility of achieving energy abundance during periods of solar absence, such as during the night or on cloudy days [5], [10].

There are three forms of thermal energy storage: sensible, latent, and thermochemical. Among TES systems, latent heat storage (LHS) has gained significant attention because it requires a smaller volume to store thermal energy and occurs at nearly constant temperatures [11]-[13].

LHS using Phase Change Materials (PCMs) is widely employed in converting and utilizing solar energy and other renewable energies, various waste heat recovery systems, and off-peak electricity storage [14][15]. It is considered one of the most efficient techniques for storing thermal energy during periods of solar availability and utilizing it during periods of solar absence, such as cloudy days or nighttime [16]. This is due to its advantages, including high energy storage density and consistent operational characteristics during the solidification and melting processes [17][16].

Given the multiple advantages of solar energy in terms of economics and the environment, and in order to utilize it during periods of solar absence (such as nighttime) or under cloudy weather conditions, researchers have been studying useful methods for heat storage to enhance the efficiency of PTCs. One such method is latent heat storage using Phase Change Materials (PCMs) as an energy storage system [18][19][20]–[23][16].

In a 2020 experimental and numerical study conducted by Djemaa Guerraiche et al., the effect of using a PCM mixture in PTCs composed of 60% $NaNO_3$ and 40% KNO_3 was investigated [24]. The results of this study demonstrated that the utilization of PCM increased the efficiency of PTCs by up to 15%.

In 2015, M.A. Kibria et al. found in their study that the combination of PCM with nanoparticles can enhance the thermal performance of PCM [25].

In a study conducted by Saw C. Lin and Hussain H. Al-Kayiem in 2016, it was concluded that the addition of 1% copper to paraffin wax can increase the thermal performance of a solar thermal energy storage system [26].

In 2018, S. Babu Sasi Kumar et al. conducted an experimental and investigative study on a direct cooking vessel of a Parabolic Trough Collector (PTC) system with the assistance of PCM for heat storage. They achieved a higher mass flow rate (MFR) of 0.035 kg/s, which resulted in better performance compared to MFR values of 0.045 and 0.065 kg/s, thereby achieving greater energy output [27].

In 2020, Guangjian Peng et al. conducted a comprehensive review and discussion on five aspects of PCM capsules (PCM classification, shell materials, microencapsulation techniques, characterization of microencapsulated PCMs, and thermal applications).

In order to assist researchers in the future use of this technology for thermal energy storage, they concluded that it is a promising technique. However, improvements need to be made to overcome certain obstacles, with the most significant one being the issue of supercooling, which needs to be resolved for the industrial application of microencapsulated PCM capsules. [28]

In 2021, Hazim Jassim Jaber et al. conducted an experimental study using PCM in coupled or uncoupled solar distillation systems with parabolic trough collectors (PTCs). According to the results obtained in this study, solar stills equipped with a PTC demonstrated higher temperatures and higher productivity compared to solar stills without PTCs. Additionally, they were capable of storing latent heat energy in the solar distillation unit, allowing for the continued condensation of fresh water even after sunset. The use of phase change material for heat storage helps maintain the hot water basin, enabling a longer condensation process. As a result, the evaporation rate of saline water in the basin and the condensation rate of the evaporated water in the humid air region improved, enhancing solar energy productivity by up to 42%. [29]

In 2021, Virendra Vishnu Bhagwat et al. conducted an experimental investigation in India to study the performance of a heat pipe assisted by a parabolic trough collector (PTC) coupled with phase change material (PCM) based on paraffin wax. They compared the storage system with and without fins. The maximum average temperature of the PCM was estimated to be 63 degrees Celsius and 60 degrees Celsius with and without fins, respectively. The charging efficiency and average discharging efficiency in the presence of fins were found to be 44.7% and 32.7% respectively, which were higher compared to the absence of fins. Additionally, they found that the presence of fins reduces the energy recovery period for the thermal storage device. The use of PCM, heat pipes, and fins can contribute to achieving the highest possible thermal efficiency in converting solar energy into hot water. [16]

It is preferable to choose a phase change material (PCM) that undergoes a solid-liquid or liquid-solid transition because it operates at lower pressures compared to a liquid-gas or gas-liquid transition [30]. Paraffin wax has been selected as an LHS material due to its suitable melting temperature range and relatively high latent heat. Paraffin provides the property of congruent melting, meaning it undergoes a phase change while preserving its chemical properties [31]. Additionally, paraffin is chemically stable, non-toxic, and non-corrosive [32][16].

In order to study and improve the thermal energy storage mechanism of solar energy collected by PTC (Parabolic Trough Collector) for utilization during periods of solar radiation absence, low-cost paraffin wax has been used as the material.

This research presents an experimental and theoretical study, along with simulations using MATLAB software, to test the performance of thermal energy storage using paraffin wax as a PCM for latent heat storage in a tank coupled with a PTC system. The study focuses on the effectiveness of using paraffin wax as a means to compensate for intermittent solar radiation during periods of solar absence. The paraffin wax is added as a surrounding layer directly in the tank, between the inner and outer surfaces, and its impact on the operation of the solar system is investigated. Additionally, a numerical model is developed for modeling the system using paraffin wax, and the validity of this model is verified through experimental work.

This research provides an experimental and theoretical study, along with MATLAB simulations, to examine the performance of thermal energy storage using paraffin wax as a PCM for latent heat storage in a tank coupled with a PTC system. The study focuses on assessing the effectiveness of paraffin wax as a means to compensate for intermittent solar radiation during periods of solar absence. The paraffin wax is added as a surrounding layer directly in the tank, between the inner and outer surfaces, and its impact on the operation of the solar system is investigated. Additionally, a numerical model is developed for modeling the system using paraffin wax, and the validity of this model is verified through experimental work.

2- Materials and Methods

Paraffin wax is considered a suitable phase change material (PCM) for low-temperature solar energy applications due to its low melting range (the specific paraffin used has a melting point of 52-54 degrees Celsius). Figure 1 and Figure 2 illustrate the paraffin wax used in the experimental work and the thermal tank containing the phase change material (paraffin wax), respectively.

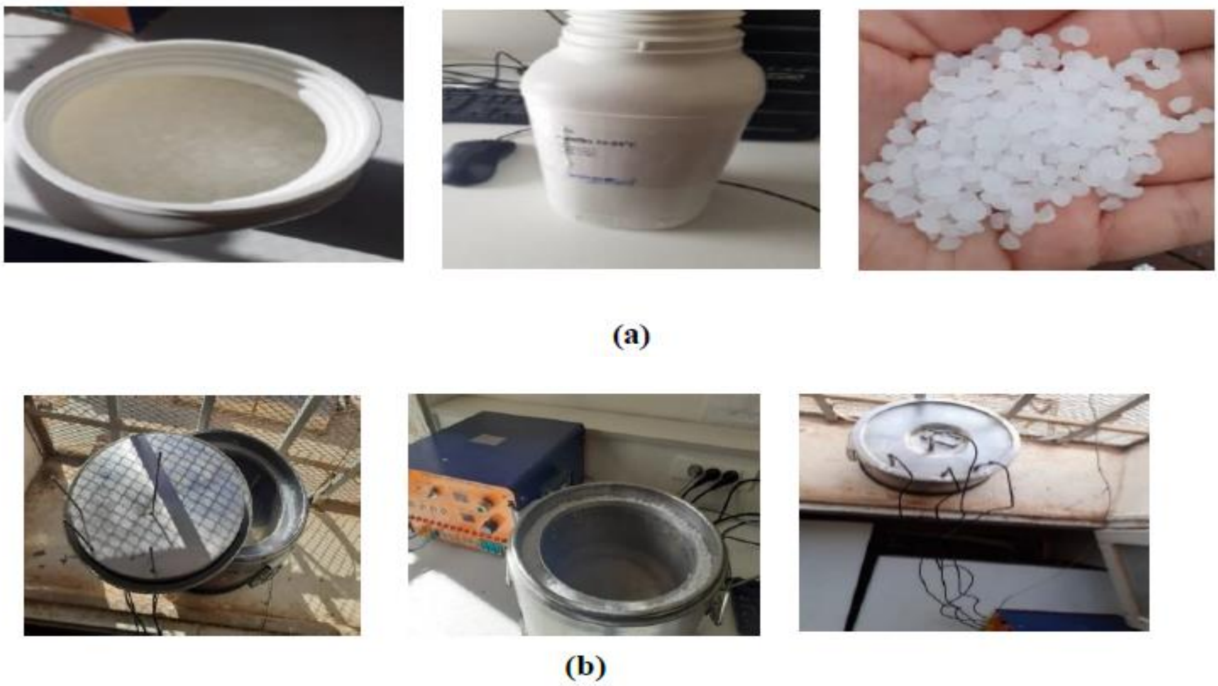

Figure. 1 **(a)** Paraffin wax used, **(b)** Thermal storage tank.

Table.1 illustrates the thermal and physical properties of the PCM used and the operating fluid.

Property	Material	Density (kg/m3)	Thermal conductivity(W/m K)	Specific heat, (kJ/kgK)	Latent heat, (kJ/kg)	Viscosity (Pa s)
PCM 54-52	Paraffin Wax	(solid)876 (liquid) 795	0.39(solid) 0.21(liquid)	2.29 (solid) 2.1(liquid)	190	3.09×10^{-3}
WorkingFluid	Water(liquid)	996.6	0.6132	4.18	2434.9	8.614×10^{-4}

The main components used and relied upon are a cylindrical tank for PCM filling for thermal energy storage and a PTC for water heating. Inox (stainless steel) is used as the material for manufacturing the PTC due to its high thermal conductivity [16]. An iron support is used for structural support. The dimensions and advantages of the PTC and the tank are mentioned in **Tables 2** and **3** below:

Table.2 Heat tank dimensions

The material of manufacture	**Inox**
external diameter r_2 (m)	**0.30**
Internal diameter r_1 (m)	**0.26**
tank thickness $(r_2-r_1)=e$ (m)	**0.02**
The inner length of the tank h_1 (m)	**0.25**
The outer length of the tank h_2 (m)	**0.27**

The material of manufacture	nox
Parabola equation (m)	$y = \frac{1}{4.f}x^2$
Length L(m)	2
Width W (m)	1.8
aperture space A_{ap} (m^2)	3.6

Table.3 Dimensions and parameters of the PTC

3. Parabolic Trough Collector (PTC) Coupled with Latent Heat Thermal Energy Storage:

3.1 experimental setup and methodology

The main components of the implemented experimental setup are a cylindrical thermal storage tank, containing paraffin wax to enhance thermal storage, a Parabolic Trough Collector (PTC), a water pump, and a flow meter device (BAMO). Paraffin wax and water are filled in the storage tank as heat transfer fluids (HTF). The storage tank is made of mild steel with an outer diameter of approximately 0.30 m, an inner diameter of 0.26 m, a height of approximately 0.25 m, and a wall thickness of 0.02 m.

Water is filled in the internal storage tank, and the space between the inner and outer tanks is filled with paraffin wax. Solar radiation is concentrated through solar tracking of the PTC along an east-west axis, following the direction from east to west of the sun. On the level of the absorption tube installed in the linear axis of the reflective surface PTC collector, the heat transfer fluid (HTF) absorbs heat from the absorption tube. After exiting the tank and flowing towards the PTC, the HTF returns to the tank, and this process continues in a closed-loop cycle from sunrise to sunset.

1. Parabolic Trough Collecter 2. Copper absorber tube, 3. Glass envelope, 4. Water storage tank, 5. Pump, 6. flow meter device., 7. Arduino 8. computer, a,b,c,d,e Thermocouples.

(A) Photographic view of the experimental setup. (B) The schematic diagram of the experimental setup

Figure.2 The experimental setup of the PTC solar collector coupled with the thermal storage tank to enhance latent heat thermal energy storage.

This system goes through the charging period with the following:

Water flows from the tank into the absorption tube located at the focal line, where solar radiation is concentrated. The heat from the concentrated solar radiation is transferred to the water, causing it to heat up.

The heated water then transfers its heat to the phase change material (paraffin wax) present in the storage tank and surrounding it. This gradually raises the temperature of the paraffin wax.

As the temperature of the paraffin wax increases, it begins to melt during the phase change stage. The thermal energy is stored in the form of sensible and latent heat, with the maximum storage capacity reached around noon.

This charging phase continues from sunrise to sunset, during which the paraffin wax undergoes complete transformation into the liquid state.

4. Mathematical formulation

In this study, we assume the following hypotheses during the storage and unloading phase:

- Clear day without clouds
- Materials show isotropic features.
- During heat transmission, a quasi-steady state is maintained.
- In heat pipes, longitudinal axial conduction is neglected.

5. Analytical Study and Thermal Storage Modelin

- Energy balancing of PTC components

For fluid (f)

$$\dot{m}_f C_{p_f}\left(T_f^t(j) - T_f^t(j-1)\right) = h_{conv_{(r\to f)}}.\Delta x.\pi.D_{r_{int}}.T_r - h_{conv_{(r\to f)}}.\Delta x.\pi.D_{r_{int}}.T_f \quad (01)$$

For the absorber tube (r)

$$\frac{\rho_r A_r C_{p_r}}{\Delta t}\left(T_r^t(j) - T_r^{t-\Delta t}(j)\right) = IC_g \tau_e \alpha_r \rho^{\circ} \pi D_{r_{ext}} + \left[h_{conv_{(r\to e)}} + h_{rad_{(r\to e)}}\right].\pi.D_{r_{ext}} T_e$$
$$-\left[\left(h_{conv_{(r\to e)}} + h_{rad_{(r\to e)}}\right) D_{r_{ext}} + h_{conv_{(r\to f)}}.D_{r_{int}}\right].\pi.T_r + h_{conv_{(r\to f)}}.\pi.D_{r_{int}} T_f \quad (02)$$

For the glass envelope (e)

$$\frac{\rho_r A_r C_{p_e}}{\Delta t}\left(T_e^t(j) - T_e^{t-\Delta t}(j)\right) = IC_g \alpha_e \rho^{\circ} \pi D_{e_{ext}} + \left[h_{conv_{(e\to r)}} + h_{rad_{(e\to r)}}\right].\pi.D_{e_{ext}} T_r$$
$$-\left[\left(h_{conv_{(e\to r)}} + h_{rad_{(e\to r)}}\right) D_{e_{ext}} + h_{conv_{(e\to amb)}}.D_{e_{ext}} + h_{rad_{(e\to Sky)}}.D_{e_{ext}}\right].\pi.T_e$$
$$+\left[\left(h_{conv_{(e\to amb)}} T_{amb}\right) + \left(h_{rad_{(e\to sky)}} T_{sky}\right)\right]\pi.D_{e_{ext}} \quad (03)$$

The latent heat storage equation is of the following form:

$$E = \int_{T_{froid}}^{T_{fusion}} m\, C_{ps}\, dT + m\, \Delta L + \int_{T_{fusion}}^{T_{chaud}} m\, C_{pl}\, dT \qquad (04)$$

6. Discussion of Results

The results of the experiments conducted in the Wargla region in December are presented and discussed, as the demand for hot water is higher during the winter season. In this section, the typical daily time interval is defined for each experiment, ranging from 07:00 to 17:00 local time. The peak solar radiation intensity reached approximately 690 W/m2 during the study days. The experiments were conducted outdoors, with and without PCM in the thermal storage tank, while adjusting the water flow rate, which serves as the heat transfer fluid (HTF).

After conducting the theoretical study, simulations, and experimental investigations, various parameters were recorded and analyzed. These parameters include solar radiation intensity (Id), temperature variations of the absorber tube (T_{ob}), temperature of the heat transfer fluid (T_f), glass cover temperature (T_e), useful heat gain (U_h), hourly solar energy collected (E_{ch}), hourly solar energy stored (E_{sth}), charging efficiency (η_{ch}), water inlet temperature into the tank (T_{fint}), water outlet temperature from the tank (T_{fout}), temperature of the phase change material (T_{PCM}), and temperature of the stored water inside the tank (T_{fstPCM}).

The results are presented in the following figures

6.1 Verification of Simulation Program Validity

Figure.3 shows the variation in experimental and simulated solar radiation values on December 28th. The concentrated solar radiation increases, reaching its peak at noon with values of 2600 W/m2 and 2688 W/m2 for the experimental and simulated data, respectively. This difference of approximately 288 W/m2 can be attributed to the weather conditions on the day of the experiment (a cloudy day). After 13:00, the solar radiation gradually decreases until sunset due to the daily pattern of solar radiation values and the effect of the solar incidence angle. At noon, when the solar incidence angle approaches 0°, maximum solar radiation is collected on the PTC collector.

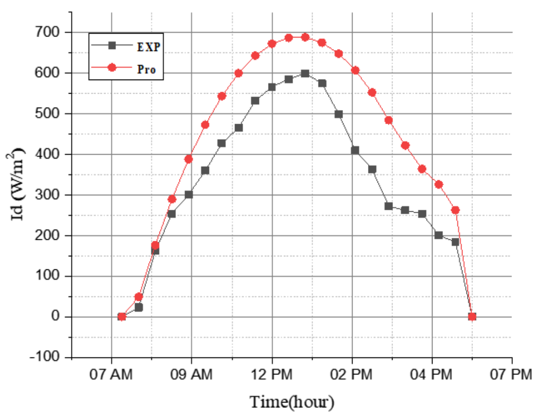

Figure.3 variations in experimental solar radiation values and simulated values.

Figure.4 shows the variations in the outlet temperatures of the absorber tube for both experimental and simulated values during the charging Period. The outlet temperatures increase from 08:00 am until noon, reaching a maximum value of around 40°C in both cases. There is a slight difference due to the variation in solar radiation intensity between the theoretical and experimental values during the charging period (notably following the trend of solar radiation, which also reaches its maximum at noon). Afterward, the temperatures gradually decrease, reaching a minimum value of approximately 32.5°C at sunset.

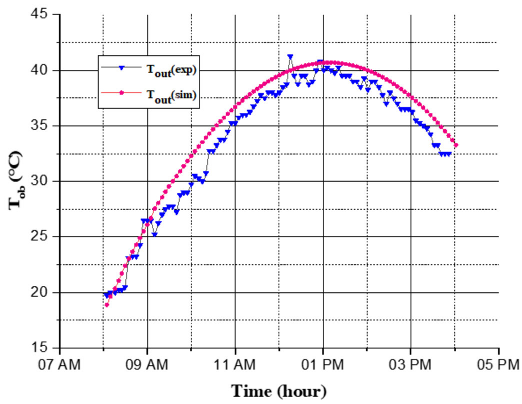

Figure.4 Variation of experimental and simulated outlet temperature of the absorber tube.

Through the previous **Figures 3** and **4**, we verify the validity of the simulation program.

6.2 The effect of mass flow rate of water on temperatures during the charging Period (simulations)

Figures 5 and **6** illustrate the effect of varying the mass flow rate of the working fluid (water) on the temperatures of the glass cover T_e, water T_f, and absorber tube T_{ob} of the PTC collector with dimensions of 6m x 3m. The temperatures increase until they reach their maximum values at solar noon. The absorber tube exhibits the highest temperature, followed by the water, and then the glass cover. This temperature variation is attributed to heat losses to the ambient air.

Figure .7 also presents a comparison of temperature variations for the water at two different flow rates. It shows that at a flow rate of 0.05Kg/s, the water temperature reached 132.6°C, while at a flow rate of 0.1Kg/s, it did not exceed 83.16°C, which is lower by 37.28%. This is because the water, at the lower flow rate, takes longer to transfer through the absorber tube, resulting in greater heat absorption along the solar center.

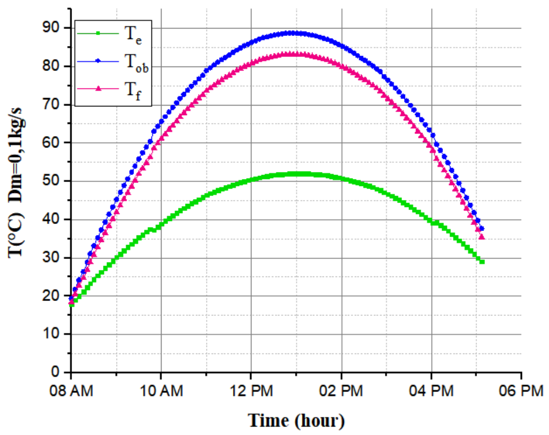

Figure.5 The effect of a mass flow rate of 0.1 kg/s on temperature variations.

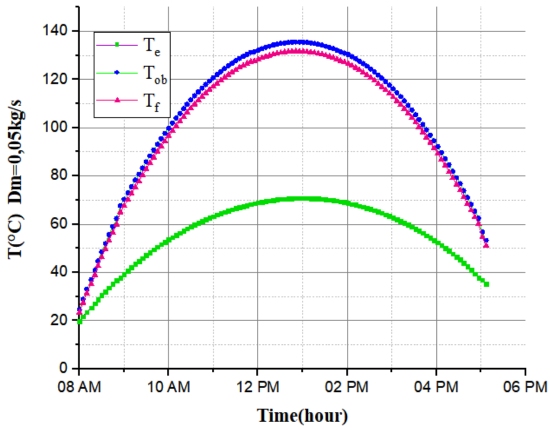

Figure.6 The effect of a mass flow rate of 0.05 kg/s on temperature variations.

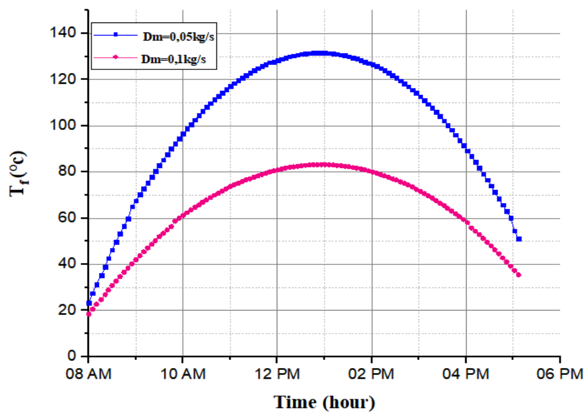

Figure.7 The comparison of temperature variations of water for two different flow rates.

The Useful heat gain is the solar energy absorbed by the circulating water as it flows through the absorber tube, and it is calculated using the following relationship (1) as follows[33]:

$$\mathbf{U_h = mC_p(T_0 - T_i)} \qquad \textbf{(05)}$$

The solar energy collected per hour is the accumulation of solar energy over a time period of one hour [33], and it is calculated using the following relationship (2) as follows:

$$\mathbf{Ec_h = \left[\frac{mC_p(T_0 - T_i)_{j+1} + mC_p(T_0 - T_i)_j}{2}\right].3600} \qquad \textbf{(06)}$$

The solar energy stored per hour is the energy stored in the water storage tank over a time period of one hour [34], and it is calculated using the following relationship (3) as follows:

$$\mathbf{Est_h = m_{st}.C_{p,st}.\left(T_{st,j+1} - T_{st,j}\right)} \qquad \textbf{(07)}$$

The charging efficiency is the ratio of the solar energy stored per hour in the water storage tank to the solar energy collected per hour [34], and it is calculated using the following relationship (4) as follows:

$$\eta_{ch} = \frac{E_{st}}{E_c} \qquad \textbf{(08)}$$

Figures 8 and **9** illustrate the variation of useful heat gain over time for the absorber tube in the absence and presence of the storage material (paraffin wax) respectively. In the absence of the storage material, we observe a gradual increase in the useful heat gain over time from 07:00 until noon, reaching its peak at 864.70W. Then, it starts to decrease until sunset due to heat losses.

On the other hand, in the presence of the storage material, we observe variation in the Useful heat gain over time, with oscillations between minimum and maximum values. This is due to the transfer of Useful heat from the solar energy to the fluid first and then its transfer from the fluid to the storage material until thermal equilibrium is reached between them. This process continues continuously until sunset. It is worth noting that the initial values of Useful heat gain are relatively low and gradually increase over time. The heat gain reaches higher values at 12:52 PM, reaching 4738.38 W and 5585.64 W at 15:29 PM after noon. This is due to the transfer of useful heat from the collected solar energy to the fluid on one hand, and from the fluid to the storage material on the other hand. After reaching its peak, the heat gain gradually decreases due to heat losses, but it remains relatively high compared to the initial values before noon.

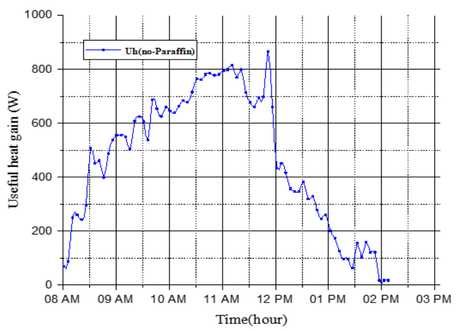

Figure.8 the variation of useful heat gain over time in the absence of the storage material .

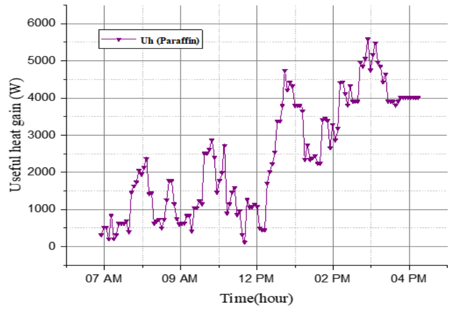

Figure.9 The variation of useful heat gain over time in the presence of the storage material (paraffin wax).

Figures 10 and **11** demonstrate the variation of solar energy collected each hour as time in the absence of the storage material (air) and in the presence of the storage material (paraffin wax), respectively. In the case of the absence of paraffin wax, the solar energy collected each hour as time increases from 7:00 am until it reaches its peak at 11:00 am, with a value of 2712.88 KJ, and then it decreases. Thus, the solar energy collected each hour over time follows the changes in incident solar radiation and the gain of useful heat

In the presence of paraffin wax, we observe the variation of solar energy collected each hour over time. The solar energy collected each hour over time increases from 7:00 am until it reaches its peak during the time period between 2:00 pm and 3:00 pm, with a value of 3378.58 kJ. Thus, the solar energy collected each hour over time follows the changes in the gain of useful heat as well.

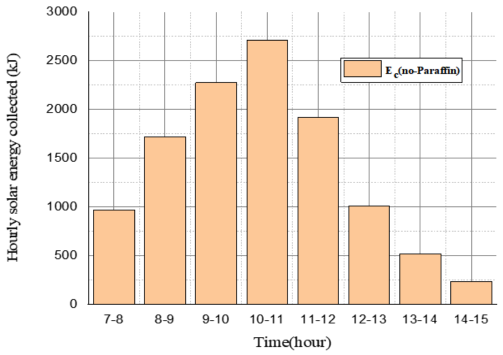

Figure.10 The variation of solar energy collected each hour over time. in the absence of a storage material (presence of air).

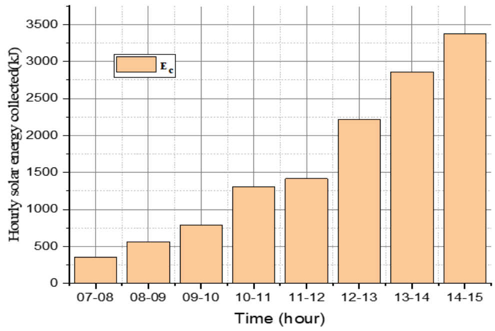

Figure.11 The variation of solar energy collected each hour over time. in the presence of a storage material (paraffin wax).

Figure.12 illustrates the variation of stored solar energy each hour as time in the presence of a storage material (paraffin wax). The stored solar energy increases more rapidly from 7:00 AM to 9:00 AM. It reaches its peak at 10:00 AM, estimated at 523 KJ. After that, it gradually decreases and reaches its lowest value at 3:00 PM, estimated at 20.92 KJ.

It is observed that the solar energy stored each hour varies in the same direction as the pattern of useful heat gain changes.

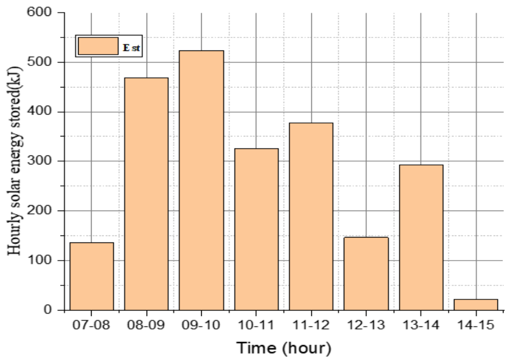

Figure.12 The variation of solar energy stored each hour in the presence of the storage material (paraffin wax).

From **Figures 13** and **14**, it can be observed that the charging efficiency reaches its maximum value of 58.29% at the beginning of the experiment in the absence of the storage material. This is due to the low heat losses resulting from the small temperature difference between the fluid and the surrounding air. However, over time, the efficiency decreases due to increasing heat losses.

On the other hand, in the presence of the storage material, the charging efficiency increases and reaches a peak value of 82.96%. This is attributed to achieving thermal equilibrium between the fluid and the storage material. However, over time, the efficiency decreases due to heat exchange between the fluid and the storage material.

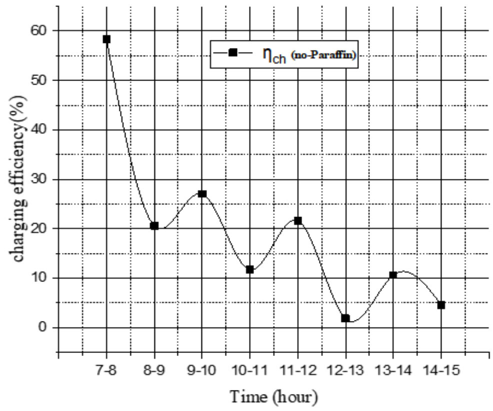

Figure.13 The variation of charging efficiency with time in the absence of the storage material(presence of air).

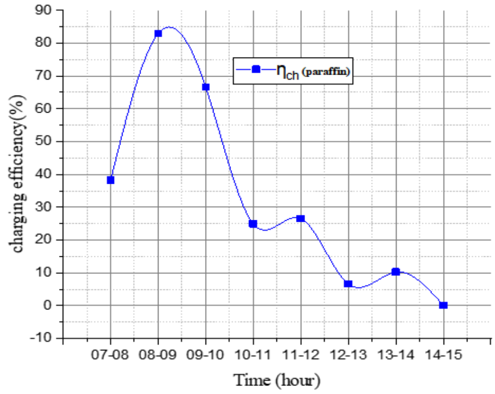

Figure.14 The variation of charging efficiency with time in the presence of the storage material

Figure.15 shows the variations in temperatures of the water inlet and outlet Tfint, Tfout, paraffin wax $T_{Paraffin}$, and the stored water inside the thermal storage tank $Tfst_{Paraffin}$ during the charging phase in the presence of the storage material (paraffin wax). The temperatures increase from 7:00 AM to noon, reaching their maximum values. After that, they start to decrease.

Meanwhile, we observe an increase followed by a nearly constant temperature for the paraffin wax $T_{Paraffin}$ at around 54°C from 11:36 AM to 1:11 PM. This stability is attributed to the phase change of the paraffin wax from a solid-liquid state.

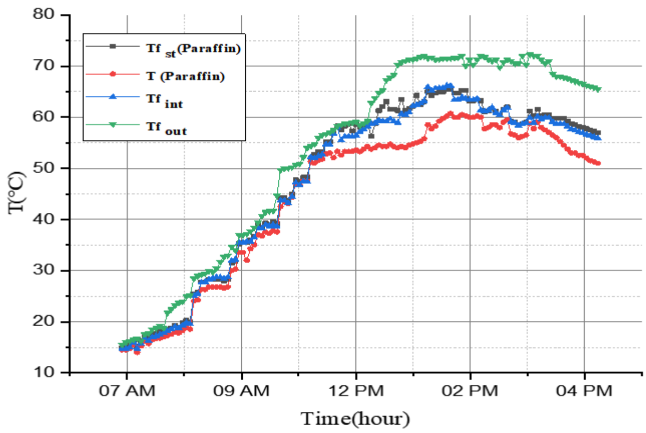

Figure.15 The variation of temperatures over time in the presence of the storage material (paraffin wax).

7- Conclusion

In this study, PTC was integrated with a thermal storage system, and a theoretical and experimental investigation was conducted to evaluate the performance and effectiveness of thermal storage using paraffin wax as a phase change material (PCM) in the form of latent heat. This system was implemented using a tank coupled with the PTC solar collector to compensate for interruptions in energy supply during periods of solar absence. The following conclusions were derived:

• The temperature changes of the water during the charging phase differed depending on the flow rate. At a flow rate of 0.05Kg/s, the temperature reached 132.6°C. However, at a flow rate of 0.1Kg/s, it did not exceed 83.16°C, indicating a decrease of 37.28 %in temperature.

• It was observed that the Useful heat gain reaches its maximum value of 864.70 W at 12:15PM in the absence of the storage material, then it starts to decrease after noon. However, in the presence of the storage material, the Useful heat gain continues to increase after noon and reaches a value of 5585.64W.

• In the absence of using paraffin as storage material, the collected solar energy each hour reached its maximum value of 2712.88 KJ from 10:00 to 11:00 am. However, when using the storage material, it reached 3378.58 KJ during the period from 14:00 to 15:00 pm.

• The solar energy stored each hour reached 523 kJ when using the paraffin from 09:00 to 10:00am.

• The charging efficiency reached its maximum value of 58.29% in the absence of using paraffin, while it reached a maximum value of 82.96% when using paraffin. Therefore, using paraffin significantly improved the charging efficiency.

• When using paraffin as a storage material, the maximum value of the outlet water temperature was 72.65 °C, and the water temperature inside the water storage tank was 65.5 °C.

• The collected solar energy each hour is influenced by changes in solar radiation.

• Through experimental and theoretical studies, we can select the appropriate storage material based on the desired temperature, considering its melting and freezing range.

Abbreviations		**Nomenclature**		
		The symbol	**The amount**	**Unity in the international system**
PTC	**Parabolic Trough Collector**			
		m	**Mass**	**kg**
HTF	**Heat Transfer Fluid**	c_p	**Heat capacity**	**J/kg.K**

PCM	Phase change material	T	temperature	°C
Guide	(lowercase letters)	A	Space	m^2
f	Fluid	ρ	Volumetric mass	Kg/m^3
r	Absorbent tube	I	The intensity of direct solar radiation	W/m^2
e	The glass envelope	C_g	The geometric focus of the solar collector	/
amb	Ambient air	τ	Transmittance coefficient	/
sky	The sky	α	Absorption coefficient	/
conv	convection	ρ'	Reflection coefficient	/
rad	Heat radiation	D	Diameter	m
ext	external	h	Heat transfer coefficient	$W/m^2.K$
int	Internal			
out	outlet			

References

[1] S. C. K. N.L. Panwar and Surendra Kothari., “Role of renewable energy sources in environmental protection: A review,” *Renew. Sustain. Energy Rev.*, vol. 15, pp. 1513–1524, 2011, doi: doi:10.1016/j.rser.2010.11.037.

[2] Weston A. Hermann, “Quantifying global exergy resources,” *Energy*, vol. 31, pp. 1685–1702, 2006, doi: doi:10.1016/j.energy.2005.09.006.

[3] R. Elarem *et al.*, “Numerical study of an Evacuated Tube Solar Collector incorporating a Nano-PCM as a latent heat storage system,” *Case Stud. Therm. Eng.*, vol. 24, p. 100859, 2021, doi: 10.1016/j.csite.2021.100859.

[4] HANS MÜLLER-STEINHAGEN FREng AND FRANZ TRIEB, *Concentrating solar power A review of the technology*. Institute of Technical Thermodynamics, German Aerospace Centre: Stuttgart, Germany, 2004; p. 9. Quarterly of the Royal Academy of Engineering Ingenia 18, February/March 2004.

[5] R. S. Md Tasbirul Islam, Nazmul Huda, A.B. Abdullah, “A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends,” *Renew. Sustain. Energy Rev.*, vol. 91, pp. 987–1018, 2018, doi: . https://doi.org/10.1016/j.rser.2018.04.097.

[6] M. E. Soudani, K. E. Aiadi, and D. Bechki, “Water heating by Parabolic Trough Collector with storage in the Ouargla region of Algerian Sahara,” *Mater. Today Proc.*, vol. 24, no. xxxx, pp. 137–139, 2020, doi: 10.1016/j.matpr.2019.07.707.

[7] H. H. H. N. S. H. N. L. and M. S. I. R. Shaharin A. Sulaiman, “Effects of Dust on the Performance of PV Panels,” *World Academy of Science, Engineering and Technology* . pp. 588–593, 2011.

[8] S. C. Mohammed Elbar Soudani, Kamal Eddine Aiadi, Djamel Bechki, “Experimental and theoretical study of Parabolic trough collector (PTC) with a flat glass cover in the region of algerian sahara (Ouargla),” *Mech. Sci. Technol.*, vol. 31, pp. 4003–4009, 2017.

[9] BECHKI Djamel, “Etude comparative et optimisation des procédés de distillation solaire en vue de la production d ’ eau potable dans les zones arides sahariennes,” University HADJ LAKHDAR BATNA, 2011.

[10] I. D. Onder Kizilkan , Ahmet Kabul, “Development and performance assessment of a parabolic trough solar collector-based integrated system for an ice-cream factory Onder,” *Energy*, vol. 100, pp. 167–176, 2016, doi: http://dx.doi.org/10.1016/j.energy.2016.01.098.

[11] M. A. B. S.M. Shalaby, “Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium,” *Energy Convers. Manag.*, vol. 83, pp. 1–8, 2014, doi: http://dx.doi.org/10.1016/j.enconman.2014.03.043.

[12] D. G. kamel. Azzouz, D. Leducq, “Performance enhancement of a household refrigerator by addition of latent heat storage,” *ScienceDirect*, vol. 31, pp. 892–901, 2008, doi: 10.1016/j.ijrefrig.2007.09.007.

[13] R. V. S. V. Pandiyarajan , M. Chinna Pandian , E. Malan , R. Velraj, “Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system,” *Appl. Energy*, vol. 88, pp. 77–87, 2011, doi: 10.1016/j.apenergy.2010.07.023.

[14] C. M. Zhongliang Liu, Zengyi Wang, “An experimental study on heat transfer characteristics of heat pipe heat exchanger with latent heat storage. Part I: Charging only and discharging only modes,” *Energy Convers. Manag.*, vol. 47, pp. 944–966, 2006, doi: 10.1016/j.enconman.2005.06.004.

[15] M. S. and A. M. Jeroen Mol, “Numerical Modeling of Thermal Storage Performance of Encapsulated PCM Particles in an Unstructured Packed Bed,” *ener*, 2020, doi: doi:10.3390/en13236413.

[16] A. C. c Virendra Vishnu Bhagwat a, Sujit Roy a, Biplab Das a, b, Nikhilkumar Shah b, “Performance of finned heat pipe assisted parabolic trough solar collector system under the

climatic condition of North East India," *Sustain. Energy Technol. Assessments*, vol. 45, p. 101171, 2021, doi: https://doi.org/10.1016/j.seta.2021.101171.

[17] A. Sarri, D. Bechki, S. Boughali, and H. Bouguettaia, "review on thermal insulation of buildings with phase change materials: incorporation methods and applications," *J. Fundam. Appl. Sci.*, 2019, doi: http://dx.doi.org/10.4314/jfas.v11i1.17.

[18] M. S. M. Khodadadi , Seyyed Ali Farshad , Z. Ebrahimpour, "Thermal performance of nanofluid with employing of NEPCM in a PVT-LFR system," *Sustain. Energy Technol. Assessments*, vol. 47, 2021, doi: https://doi.org/10.1016/j.seta.2021.101340.

[19] R. Bayón, E. Rojas, L. Valenzuela, E. Zarza, and J. León, "Analysis of the experimental behaviour of a 100 kWth latent heat storage system for direct steam generation in solar thermal power plants," *Appl. Therm. Eng.*, vol. 30, no. 17–18, pp. 2643–2651, 2010, doi: 10.1016/j.applthermaleng.2010.07.011.

[20] M. G. V. Eleni Douvi, Christos Pagkalos, George Dogkas, Maria K. Koukou, Vassilis N. Stathopoulos, Yiannis Caouris, "Phase change materials in solar domestic hot water systems: A review," *Int. J. ofThermofluid*, vol. 10, 2021, doi: https://doi.org/10.1016/j.ijft.2021.100075.

[21] S. S. D. Vikrant P. Katekar, "A Review on Research Trends in Solar Still Designs for Domestic and Industrial Applications," *J. Pre-proof*, 2020, doi: https://doi.org/10.1016/j.jclepro.2020.120544.

[22] V. V. T. A.K. Pandey , Imtiaz Ali Laghari , R. Reji Kumar, Kapil Chopra , M. Samykano , Abdullah M. Abusorrah , Kamal Sharma, "Energy, exergy, exergoeconomic and enviroeconomic (4-E) assessment of solar water heater with/without phase change material for building and other applications: A comprehensive review," *Sustain. Energy Technol. Assessments*, vol. 45, 2021, doi: https://doi.org/10.1016/j.seta.2021.101139.

[23] M. C. R. Senthil, "Enhancement of the thermal energy storage capacity of a parabolic dish concentrated solar receiver using phase change materials," *J. Energy Storage J.*, vol. 25, 2019, doi: https://doi.org/10.1016/j.est.2019.100841.

[24] Z. D. Djemaa Guerraiche, Cherif Bougriou , Khelifa Guerraiche, Loreto Valenzuela, "Experimental and numerical study of a solar collector using phase change material as heat storage Djemaa," *J. Energy Storage*, vol. 27, 2020, doi: https://doi.org/10.1016/j.est.2019.101133 Received.

[25] I. H. S. C. M. D. M.A. Kibria, M.R. Anisur, M.H. Mahfuz, R. Saidur, "A review on thermophysical properties of nanoparticle dispersed phase change materials," *Energy Convers. Manag.*, vol. 95, 2015, doi: http://dx.doi.org/10.1016/j.enconman.2015.02.028.

[26] H. H. A.-K. Saw C. Lin, "Evaluation of copper nanoparticles – Paraffin wax compositions for solar thermal energy storage," *ScienceDirect*, vol. 132, 2016, doi: http://dx.doi.org/10.1016/j.solener.2016.03.004.

[27] Babu Sasi Kumar, "INVESTIGATIONAL STUDY FOR DIRECT COOK POT FROM PARABOLIC TROUGH COLLECTOR (PTC) ASSISTED PCMs (PHASE CHANGE

MATERIALS) HEAT STORAGE. 1S.Babu," *Int. J. Pure Appl. Math.*, vol. 118, no. Special Issue, pp. 425–437, 2018.
[28] Y. S. and Z. C. Guangjian Peng, Guijing Dou, Yahao Hu, "Phase Change Material (PCM) Microcapsules for Thermal Energy Storage," *Adv. Polym. Technol.*, 2020, doi: https://doi.org/10.1155/2020/9490873.
[29] Q. A. A. Hazim Jassim Jaber, Qais A. Rishak, "Using.PCManexperimentalstudyonsolarstillscoupledwithandwithoutaparabolictroughsolarcollector," *Basrah J. Eng. Sci.*, vol. 21, pp. 45–52, 2021, doi: DOI: 10.33971/bjes.21.2.7 CITATIONS.
[30] D. B. M. Beemkumar Nagappan, Karthikeyan Alagu, Yuvarajan Devarajan, "Energy and Exergy Analysis ofMulti-Temperature PCMs Employed in a Latent Heat Storage System and Parabolic Trough Collector," 2018, doi: https://doi.org/10.1515/jnet-2017-0066.
[31] D. B. b Atul Sharma , V.V. Tyagi , C.R. Chen, "Review on thermal energy storage with phase change materials and applications," *ScienceDirect*, vol. 13, pp. 318–345, 2009, doi: doi:10.1016/j.rser.2007.10.005.
[32] S. L. Daniel. R. Rousse, Nizar Ben Salah, "An Overview of Phase Change Materials and their Implication on Power Demand," in *IEEE Electr. Power Energy Conf. (EPEC-2009)*, 2009, pp. 1–6.
[33]A. K. Bhakta, N. K. Panday, and S. N. Singh, "Performance study of a cylindrical parabolic concentrating solar water heater with nail type twisted tape inserts in the copper absorber tube," Energies, vol. 11, no. 1, 2018, doi: 10.3390/en11010204.
[34] G. Kumaresan, R. Sridhar, and R. Velraj, "Performance studies of a solar parabolic trough collector with a thermal energy storage system," Energy, vol. 47, no. 1, pp. 395–402, Nov. 2012, doi: 10.1016/J.ENERGY.2012.09.036.