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"Enhancing Optimal Thermal Energy Storage in Solar Parabolic Concentrator System by Using Phase Change Material"

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Abstract: Solar Parabolic Trough Systems (PTS) are highly efficient solar thermal technologies for converting concentrated solar radiation into thermal energy. However, their intermittent energy production, primarily due to variations in solar availability, underscores the necessity for effective thermal energy storage (TES) solutions. Phase Change Materials (PCMs) have emerged as a promising means to store and release thermal energy efficiently. This study focuses on the critical task of optimizing PCM properties to enhance thermal energy storage within Solar Parabolic Trough Systems.

The selection and fine-tuning of PCM properties are paramount to achieving superior TES performance. Parameters under scrutiny include the melting temperature, latent heat of fusion, thermal conductivity, and cost-effectiveness. Each of these factors plays a pivotal role in the overall efficiency and economic viability of PCM-based TES systems integrated with PTS.

Through a thorough review of existing research and recent advancements in the field, this study sheds light on the profound impact of tailored PCM properties. It demonstrates how optimizing these properties can lead to substantial improvements in energy storage capacity, system efficiency, and overall cost-effectiveness. Such optimizations are crucial not only for enhancing the competitiveness of solar thermal technology but also for promoting sustainable energy utilization.

The investigation presented herein underscores the significance of PCM property optimization as a strategic pathway toward advancing solar thermal technology. By maximizing energy storage capacity, minimizing thermal losses, and optimizing cost factors, we can unlock the full potential of PTS, making them more reliable and accessible for meeting the world's growing energy demands. This research serves as a valuable resource for engineers, researchers, and stakeholders working towards the integration of PCM-based TES with solar thermal systems. Ultimately, it contributes to the realization of a cleaner, more sustainable energy future, addressing the urgent need to reduce greenhouse gas emissions and our reliance on non-renewable energy sources.

Keywords: Solar Parabolic Trough Systems, thermal energy storage, Phase Change Material (PCM), melting temperature, latent heat of fusion, thermal conductivity.

I. INTRODUCTION

The global demand for energy continues to rise, driven by population growth, industrialization, and increasing living standards. In this context, sustainable and renewable energy sources are becoming crucial to mitigate the environmental impacts of conventional fossil fuel-based energy systems. Solar energy, abundant and clean, stands out as a viable solution to meet a significant portion of this growing energy demand. Solar thermal energy, in particular, offers an effective means to harness the sun's power and convert it into usable thermal energy.

One of the key challenges in utilizing solar thermal energy is its intermittent nature due to the variability in solar irradiance. To address this issue and enhance the efficiency and effectiveness of solar thermal systems, integrating solar collectors with thermal energy storage systems is essential. Phase Change Material (PCM) based thermal energy storage is a promising technology that allows the efficient storage and retrieval of thermal energy, providing a continuous and reliable source of heat even during periods of low solar radiation.

This paper explores the integration of a solar parabolic trough collector with a Phase Change Material (PCM) based thermal energy storage system. The parabolic trough collector is a well-established solar thermal technology known for its high efficiency in concentrating solar radiation and converting it into thermal energy. On the other hand, PCM technology offers an efficient means of storing and utilizing thermal energy through phase transitions.

The integration of a PCM-based thermal energy storage system with a solar parabolic trough collector aims to maximize the utilization of solar energy by capturing excess thermal energy during peak solar hours and storing it in PCM. This stored energy can then be utilized during non-solar hours or cloudy periods, ensuring a consistent and reliable energy supply. Additionally, this integration improves the overall efficiency of the solar thermal system and contributes to the reduction of greenhouse gas emissions and reliance on non-renewable energy sources.

A. Solar Thermal Collectors

Solar thermal collectors are devices that utilize sunlight to generate thermal energy for various applications, primarily space heating, water heating, and electricity generation. They are a vital component of solar thermal systems, harnessing solar radiation and converting it into usable heat. There are several types of solar thermal collectors, including flat-plate collectors, evacuated tube collectors, parabolic troughs, and dish collectors.

Flat-plate collectors are the most common and comprise an insulated, weatherproof box with a dark absorber plate that absorbs sunlight, heating a fluid or air passing through it. Evacuated tube collectors consist of a series of glass tubes containing an absorber, maintaining high efficiency even in cold climates. Parabolic troughs use curved, mirrored reflectors to concentrate sunlight onto a receiver tube, heating a fluid inside. Dish collectors focus sunlight onto a small area, typically containing a Stirling engine or a photovoltaic cell to generate electricity.

Solar thermal collectors are essential for renewable energy production, promoting sustainability and reducing greenhouse gas emissions. Ongoing research and development aim to enhance their efficiency, cost-effectiveness, and integration into various applications.

B. Classification of Solar Thermal Collectors

Solar thermal collectors can be classified based on various criteria, including their design, the way they capture and utilize solar energy, and their specific applications. Here's a classification based on design and application:

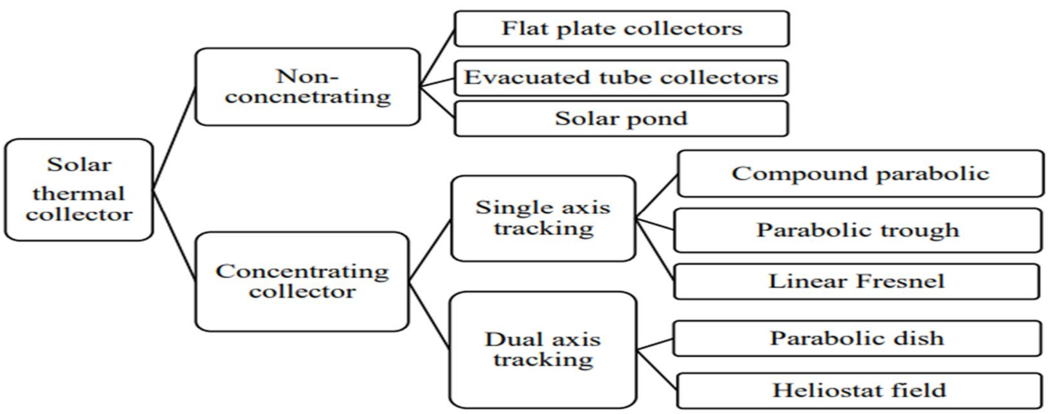


Figure 1: Classification of solar thermal collectors

C. Based on Design

1) *Flat-Plate Collectors:* Flat-plate collectors are the most common type and consist of a flat absorber plate with a transparent cover and insulation. - The absorber plate absorbs solar energy and transfers it to a fluid (air, water, or another heat transfer fluid) for heating purposes.
2) *Evacuated Tube Collectors:* Evacuated tube collectors use rows of transparent glass tubes with an absorber tube inside each. - The vacuum between the tubes reduces heat loss and enhances thermal efficiency. - They are more efficient in capturing solar energy compared to flat-plate collectors.
3) *Parabolic Trough Collectors:* Parabolic trough collectors use parabolic-shaped mirrors to focus sunlight onto a receiver tube placed at the focal line of the parabola. - The receiver tube contains a heat transfer fluid (often oil) that is heated by concentrated sunlight. - Commonly used in large-scale solar power plants to generate electricity.
4) *Fresnel Reflectors:* Fresnel reflectors use a series of flat, narrow mirrors (Fresnel lenses) to concentrate sunlight onto a linear receiver. - They are often used in concentrated solar power (CSP) systems for electricity generation.

D. Based on Application

1) *Domestic Water Heating:* Solar collectors designed to provide hot water for residential or small-scale commercial purposes. - Usually flat-plate or evacuated tube collectors are used.
2) *Space Heating:* Solar collectors used to provide heat for space heating in buildings. - Flat-plate collectors are commonly used for this purpose.
3) *Industrial Process Heat:* Solar thermal systems designed to provide high-temperature heat for industrial processes. - Often use concentrating collectors like parabolic troughs or Fresnel reflectors.
4) *Solar Cooling:* Solar collectors used in combination with absorption chillers to provide solar-powered air conditioning or refrigeration. - Absorption chillers are typically powered by high-temperature heat from solar collectors.
5) *Electricity Generation (Concentrated Solar Power - CSP):* Solar collectors designed to generate electricity by concentrating sunlight to produce high temperatures and drive turbines. - Parabolic troughs, Fresnel reflectors, and other concentrating collectors are used.

II. MATERIALS

1) Choose a suitable PCM based on desired phase change temperature matching solar parabolic trough operating temperatures. E.g., paraffin waxes, salt hydrates, or eutectic mixtures.
2) Add thermally conductive materials (e.g., graphite, carbon nanotubes) to enhance the thermal conductivity of the PCM, improving heat transfer rates during charging and discharging.
3) Utilize nanostructured materials to enhance surface area and promote nucleation, aiding in achieving desired phase change temperatures and improving heat transfer efficiency.
4) Develop composites by combining PCMs with suitable matrices to improve structural stability, mechanical properties, and thermal conductivity.

III. METHODOLOGY

1) Conduct a thorough analysis to determine the phase transition temperature, heat of fusion, thermal conductivity, and specific heat capacity of selected PCMs.
2) Employ techniques like sol-gel, mechanical mixing, or in-situ polymerization to introduce nanomaterials or form composites with the PCM. b. Characterize the nanostructured PCM and composite materials to assess changes in properties.
3) Mix PCMs with conductive materials and analyze the thermal conductivity using appropriate methods (e.g., transient plane source technique). b. Optimize the ratio of conductive materials to achieve enhanced thermal conductivity.
4) Subject the PCMs and composites to multiple thermal cycles to assess stability, phase change temperatures, and energy storage/release capabilities. b. Evaluate any degradation or hysteresis effects over extended cycles.
5) Design and simulate the integration of optimized PCMs within the solar parabolic trough system using software like TRNSYS or SAM. b. Evaluate system performance under varying solar conditions and thermal storage requirements.
6) Conduct a detailed cost analysis considering the cost of materials, encapsulation, and potential efficiency gains to determine the cost-effectiveness of the optimized PCM.
7) Perform an environmental impact assessment to analyze the sustainability and eco-friendliness of using the optimized PCM materials.
8) Validate the optimized PCM properties in a real-world solar parabolic trough setup, analyzing performance under actual solar radiation and thermal load conditions.

A. Solar Parabolic Dish Collector

A solar parabolic dish collector, also known as a parabolic dish concentrator, is a type of solar thermal technology used to concentrate sunlight onto a small focal point to produce heat or generate electricity. The collector is designed in a parabolic shape to focus sunlight onto a receiver at the focal point.

Figure 2: Solar parabolic dish collector

Here are key components and aspects of a solar parabolic dish collector:

1) *Parabolic Dish Structure*
- The collector is shaped like a parabolic dish, resembling a large satellite dish, with a highly reflective surface to concentrate sunlight.
- The parabolic shape helps to focus sunlight from all directions onto a single point, the focal point.

2) *Reflective Surface*
- The inner surface of the parabolic dish is covered with highly reflective material, such as polished aluminum or special reflective coatings, to efficiently reflect and concentrate sunlight.

3) *Receiver at Focal Point*
- At the focal point of the parabolic dish, there is a receiver where the concentrated sunlight is directed.
- The receiver can be a thermal absorber, a Stirling engine, a Brayton cycle engine, or a photovoltaic (PV) cell, depending on the application.

4) *Thermal Absorber*
- In many solar parabolic dish systems, a thermal absorber is used to capture the concentrated sunlight and convert it into thermal energy.
- The absorber is often a pipe or receiver containing a heat transfer fluid (e.g., oil or water) that absorbs the concentrated solar heat and transfers it for further use, like electricity generation or heating.

5) *Tracking System*
- To ensure the parabolic dish is always oriented towards the sun and maximizes solar concentration, a tracking system is employed.
- The tracking system adjusts the orientation of the parabolic dish to follow the sun's movement throughout the day.

6) *Applications*
- Solar parabolic dish collectors can be used for various applications, including electricity generation, water heating, space heating, industrial process heat, and even for solar cooking.

7) *Electricity Generation*
- In electricity generation, the concentrated sunlight at the receiver is used to power a heat engine (e.g., Stirling engine or Brayton cycle engine) that drives a generator to produce electricity.

8) Efficiency and Concentration Ratio

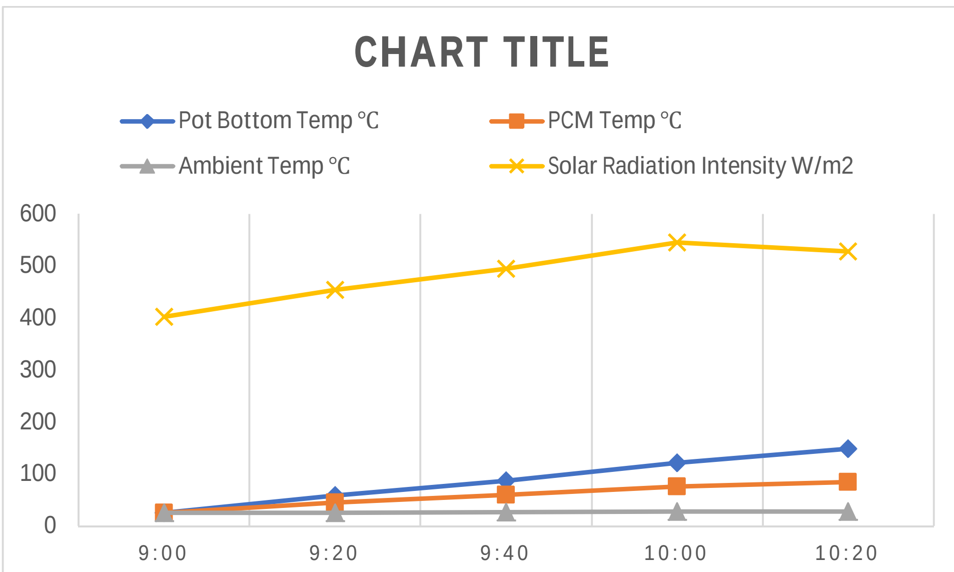
- Parabolic dish collectors can achieve very high concentration ratios, often exceeding 1000 suns, which significantly increases the temperature at the focal point and enhances efficiency.

B. Case 1 Pcm – Neopentyl glycol , cooking material- rice + water

1) Morning PCM charging

Neopentyl glycol, a phase transition substance, was filled in the outside part of the concentric cylinder type solar cooker in the experiment's initial phase. To charge the PCM at 9:00 am, a solar cooker is placed on the plate of a parabolic dish collector and exposed to solar light. At 10:20 am, the ambient temperature rose from 25°C to 28.1°C. PCM temperature began to rise at 25°C and quickly increased to 84.1°C. Similar to this, the temperature of the pot's bottom climbs from 25°C to 149°C. Morning solar radiation levels vary from 402 W/m2 to 545 W/m2.

Time	Pot Bottom Temp °C	PCM Temp °C	Ambient Temp °C	Solar Radiation Intensity W/m^2
09:00	25	25	25	402
09:20	59	45	25.4	454
09:40	87	59.3	26.3	495
10:00	122	75.6	27.2	545
10:20	149	84.1	28.1	528



Graph 1: Variation of temperature of thermal energy storage and solar radiation intensity with time.

2) Food Input Cooking time 25 min

After the PCM has been partially charged, we load the solar cooker with food (210 g of rice and 420 g of water), and solar radiation continues to fall (both direct and diffused) on the cooker. Food temperature begins to increase above the ambient temperature while PCM temperature steadily decreases, demonstrating the transmission of heat from the PCM to the food via the dividing wall. In the first 10 minutes of this phase, the PCM temperature declines from 94°C to 90.1°C before rising once more to 90°C. Due to an instantaneous heat transfer to the food, the pot's bottom temperature immediately dips to 80°C before rapidly rising to 179°C. Solar radiation has an intensity that varies from 650 W/m2 to 612 W/m2. 35 minutes pass before food reaches 35.6 °C, and the rice is deemed to be fine.

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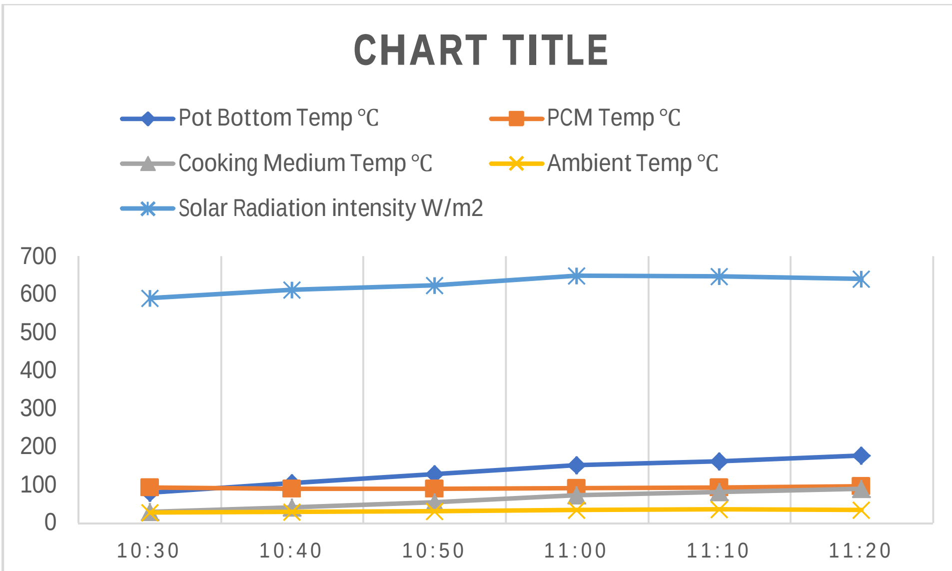
Time	Pot Bottom Temp ℃	PCM Temp ℃	Cooking Medium Temp ℃	Ambient Temp ℃	Solar Radiation intensity W/m^2
10:30	80	94	30	28.4	590
10:40	105	90.1	42	30.2	612
10:50	129	89.8	55	32	624
11:00	153	92.3	74	35	650
11:10	163	93.5	81	35.6	647
11:20	177	97.1	90	35.2	641

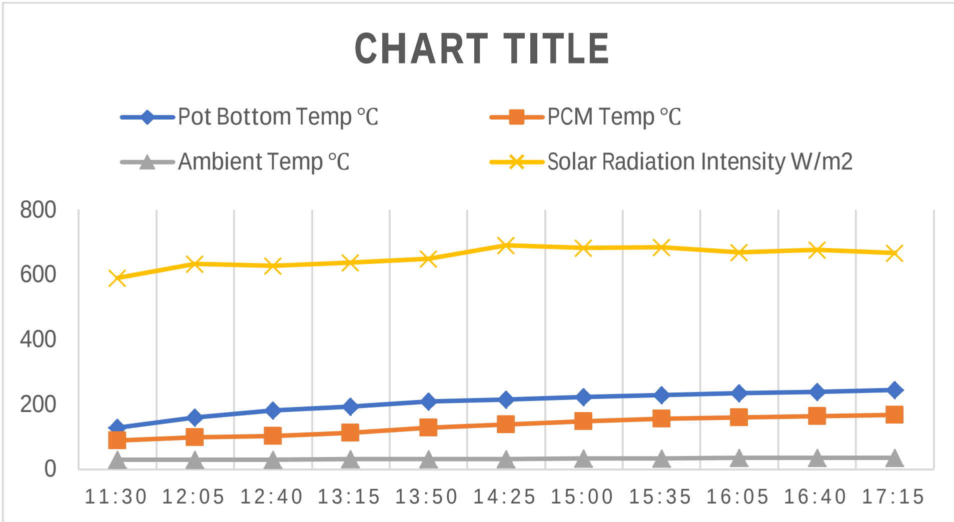


Graph 2: Variation of temperature of thermal energy storage, cooking medium and solar radiation intensity with time.

3) PCM Charging Again

In order to charge the PCM for the second round of cooking, the solar cooker was once more exposed to sun radiation. This time, PCM charging was kept going until 17:15 so that superheating could take place. The ambient temperature ranges from 30°C to 36.7°C. PCM temperature increases from 89°C to 169°C. When the PCM temperature approaches the melting point of neopentyl glycol, it increases at a decreasing rate. After the PCM melted at 13:50, its temperature began to rise again, and it eventually reached a superheated state. Due to clouds, solar radiation changes during the charging process between 590 W/m2 to 690 W/m2. A reading was obtained every 35 minutes.

Time	Pot Bottom Temp ℃	PCM Temp ℃	Ambient Temp ℃	Solar Radiation Intensity W/m^2
11:30	129	89	30	590
12:05	160	100	30.4	633
12:40	182	103	31.2	627
13:15	193	113	31.7	637
13:50	209	128	32.1	650
14:25	215	138	32.9	690
15:00	224	148	33.5	682
15:35	229	157	34.8	684
16:05	235	161	35.6	670
16:40	240	165	36.3	677
17:15	245	168	36.7	667

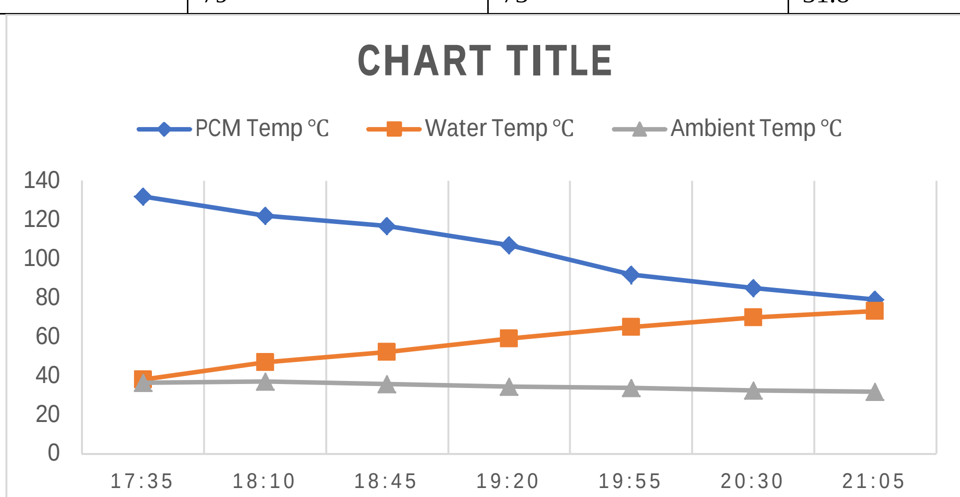


Graph 3: Variation of temperature of thermal energy storage and solar radiation intensity with time

4) PCM Discharging with Food cooking time 3 hrs50minits

Superheated PCM within a solar cooker pot that has been raised from a parabolic dish collection plate and placed inside a wooden insulation box that has been lined with thermocol sheets to boost the efficiency of the cooker. 420 gallons of water and 210 grammes of rice are placed in the solar cooker pot. As time goes on, the PCM temperature drops to 79°C as a result of heat transmission from the PCM to the cooking medium. And the cooking medium temperature rises to 73°C. Rice was discovered to be thoroughly cooked at 21:05 and the PCM temperature was 79°C, keeping food warm for the following three hours. There were readings collected every 35 minutes.

PCM discharging with water time 3 hrs			
Time	PCM Temp °C	Water Temp °C	Ambient Temp °C
17:35	132	38	36.4
18:10	122	47	36.9
18:45	117	52	35.6
19:20	107	59	34.2
19:55	92	65	33.7
20:30	85	70	32.5
21:05	79	73	31.8



Graph 4: Variation of temperature of thermal energy storage and cooking medium with time.

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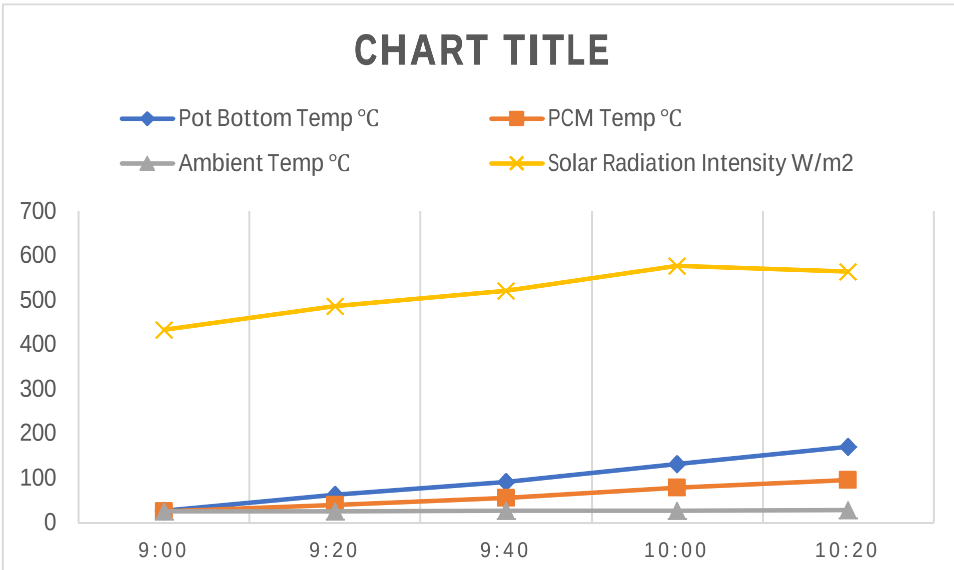
C. Case 2 - PCM – Paraffin wax (e.g. octadecane), cooking material- water

1) Morning PCM charging

In the first stage of the experiment, the concentric cylinder-shaped solar cooker's outer section was filled with paraffin wax (for example, octadecane), a phase-change substance. To charge the PCM at 9:00 am, a solar cooker is placed on the plate of a parabolic dish collector and exposed to solar light. At first, the ambient temperature was 25 °C, but by 10 °C, it had risen to 28 °C. PCM temperature began to rise at 25.2°C and quickly increased to 95°C. Similar to that, the pot's bottom temperature increases from 26 to 170 degrees Celsius. Morning solar radiation levels vary from 434 W/m2 to 577 W/m2.

Time	Pot Bottom Temp °C	PCM Temp °C	Ambient Temp °C	Solar Radiation Intensity W/m^2
9:00	26	25.2	25	434
9:20	62	39	25.6	487
9:40	92	55	26.8	521
10:00	132	79	27.2	577
10:20	170	95	28.4	564

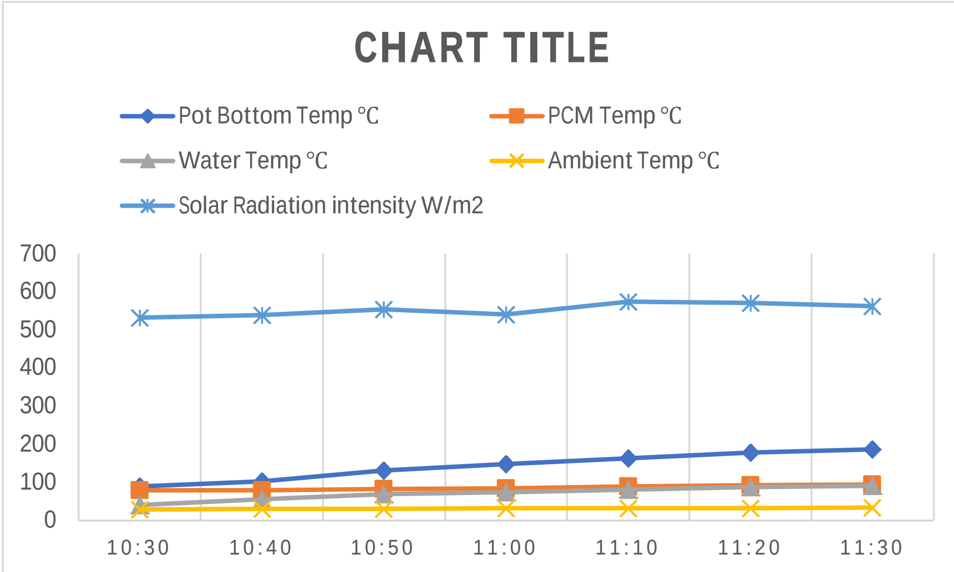


Graph 5 : Variation of temperature of thermal energy storage and solar radiation intensity with time.

2) Water Input Boiling time 35 min

After the PCM has partially charged, we fill the solar cooker with water (605 grammes), and solar radiation continues to fall (direct and diffused) on the cooker. As PCM temperature progressively falls, heat from the PCM is transferred to the water through the dividing wall, causing the water temperature to begin to increase above the ambient temperature. During this phase, the PCM temperature rises from 78°C to 90°C in 10 minutes. Due to an abrupt heat transfer to the water, the pot's bottom temperature suddenly dips to 89°C before quickly rising to 188°C. Solar radiation has an intensity that varies from 532 W/m2 to 574 W/m2. 39 minutes are needed to reach 90°C in the water. (Fig.) Morning intensity ranges from 434 W/m2 to 577 W/m2. (Fig.)

Time	Pot Bottom Temp °C	PCM Temp °C	Water Temp °C	Ambient Temp °C	Solar Radiation intensity W/m^2
10:30	89	78	39	28.3	532
10:40	101	79	54	29.5	538
10:50	130	82	68	30.3	554
11:00	147	83	74	30.8	541
11:10	162	88	80	31.2	574
11:20	178	91	87	31.6	570
11:30	185	94	90	32.4	562



Graph 6 : Variation of temperature of thermal energy storage, water and solar radiation intensity with time

3) PCM Charging again Charging time 5 hrs

The solar cooker was once more exposed to solar radiation for the second round of water heating in order to charge the PCM. This time, PCM charging was kept going until 17:25 so that superheating could take place. It is between 36°C and 38.7°C outside. PCM temperature increases from 91°C to 170°C. When the PCM temperature gets close to the melting point of paraffin wax (for example, cotadecane), it increases at a decreasing pace. After the PCM melted at 14:35, its temperature began to rise again, and it eventually reached a superheated state. During the charging phase, solar radiation ranges from 646 W/m2 to 719 W/m2. A reading was obtained every 35 minutes.

Time	Pot Bottom Temp °C	PCM Temp °C	Ambient Temp °C	Solar Radiation Intensity W/m^2
11:40	141	91	36	646
12:15	157	99	36.3	652
12:50	163	111	36.9	677
13:25	180	118	37	711
14:00	184	124	37.4	716
14:35	194	129	37.7	719
15:05	211	136	38	715
15:40	224	145	38.1	708
16:15	231	156	38.5	701
16:50	239	164	38.7	694
17:25	247	170	39	684

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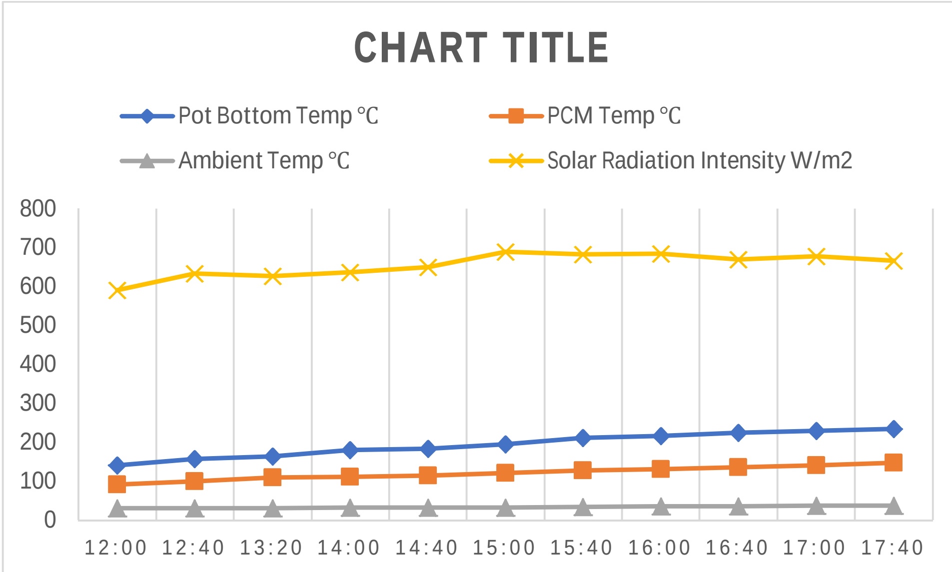
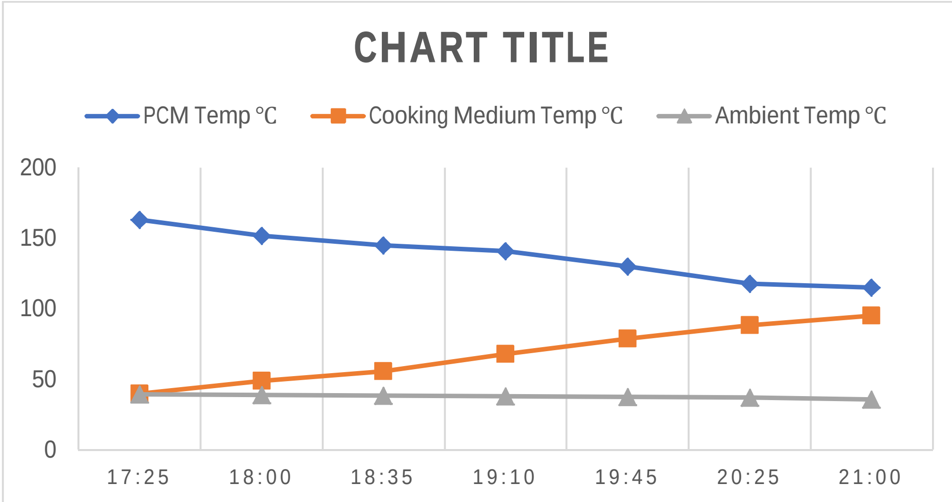


Graph 7 : Variation of temperature of thermal energy storage and solar radiation intensity with time

4) PCM discharging with water time 3 hrs

Superheated PCM within a solar cooker pot that has been raised from a parabolic dish collection plate and placed inside a wooden insulation box that has been lined with thermocol sheets to boost the efficiency of the cooker. 605 grammes of water are placed into the solar cooker pot. As time goes on, the PCM temperature drops to 115°C as a result of heat transmission from the PCM to the cooking medium. And the cooking medium temperature increases to 95.2°C. The water temperature was 95.2°C at 1:00 a.m. There were readings collected every 35 minutes. (Fig.)

Time	PCM Temp °C	Cooking Medium Temp °C	Ambient Temp °C
17:25	163	40	39.5
18:00	152	49	39
18:35	145	56	38.4
19:10	141	68	38.1
19:45	130	79	37.8
20:25	118	88.5	37.3
21:00	115	95.2	36



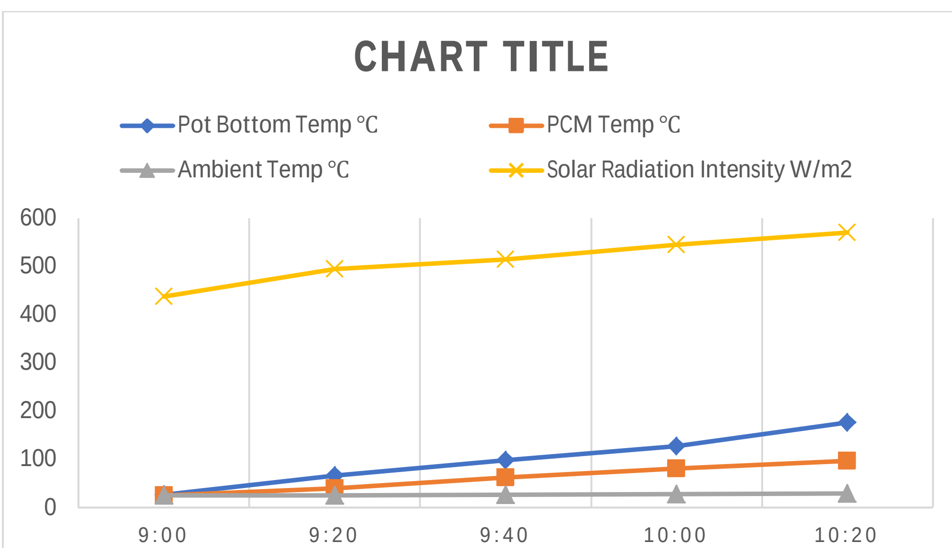
Graph 8 : Variation of temperature of thermal energy storage and water with time

D. Case 3 - PCM – Therminol VP-1(a Hight Temperature PCM) , Cooking Material- Rice + Water

1) Morning PCM Charging

In the initial stage of the experiment, concentric cylinder-shaped solar cookers were filled with phase change material, namely Therminol VP-1 (a High Temperature PCM). To charge the PCM at 9:00 am, a solar cooker is placed on the plate of a parabolic dish collector and exposed to solar light. At first, the ambient temperature was 25.2°C, but by 10:20 am, it had risen to 29.5°C. PCM temperature began to rise at 25.5°C and quickly increased to 97°C. Similar to this, the temperature of the pot's bottom increases from 26.5°C to 177°C. Morning solar radiation levels vary from 439 W/m2 to 570 W/m2.

Time	Pot Bottom Temp °C	PCM Temp °C	Ambient Temp °C	Solar Radiation Intensity W/m^2
09:00	26.5	25.5	25.2	438
09:20	66	40	25.7	495
09:40	98	62	26.3	515
10:00	127	81	27.8	545
10:20	177	97	29.5	570

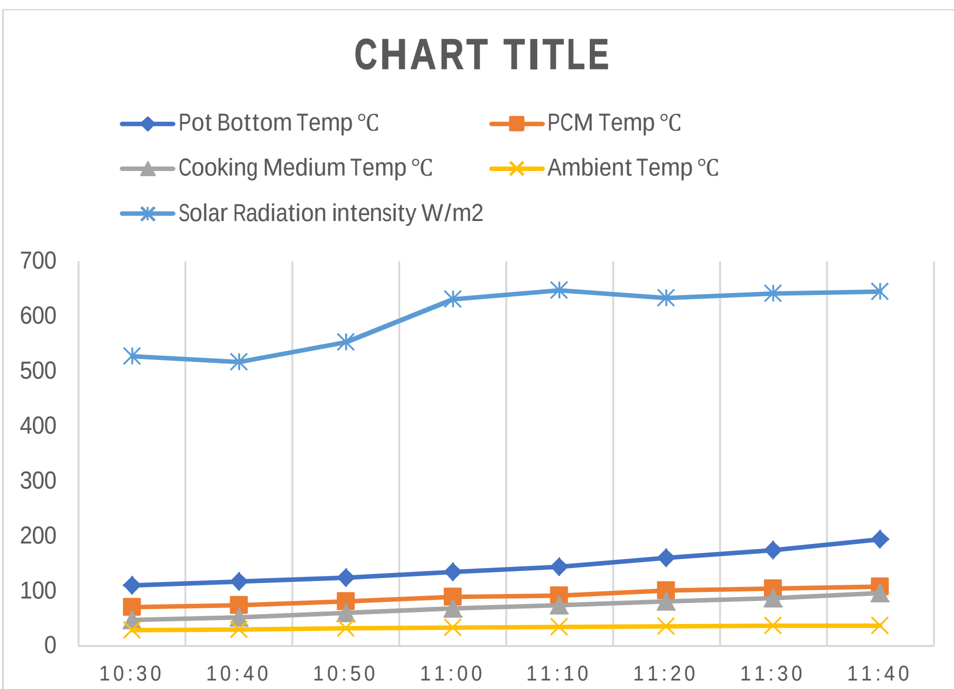


Graph 9 : Variation of temperature of thermal energy storage and solar radiation intensity with time

2) Food input Cooking Time 55 min

After the PCM has been partially charged, we load the solar cooker with food (210 g of rice and 420 g of water), and solar radiation continues to fall (both direct and diffused) on the cooker. Food temperature begins to increase above the ambient temperature while PCM temperature steadily decreases, demonstrating the transmission of heat from the PCM to the food via the dividing wall. In this phase, the PCM temperature increases 10 degrees, from 71 to 75. Due to a rapid heat transmission to the food, the temperature at the bottom of the pot lowers quickly to 110°C before rising again to 194°C. Solar radiation has an intensity that varies from 517 W/m2 to 645 W/m2. Rice is discovered to be well cooked and food temperature rises to 97°C in 60 minutes. (Fig.)

Time	Pot Bottom Temp °C	PCM Temp °C	Cooking Medium Temp °C	Ambient Temp °C	Solar Radiation intensity W/m^2
10:30	110	71	48	29.2	527
10:40	117	75	52	29.8	517
10:50	125	81	61	32.4	553
11:00	135	90	69	34.2	631
11:10	144	92	74	35.3	647
11:20	161	101	81	36.1	634
11:30	175	105	87	36.7	642
11:40	194	108	97	37.1	645

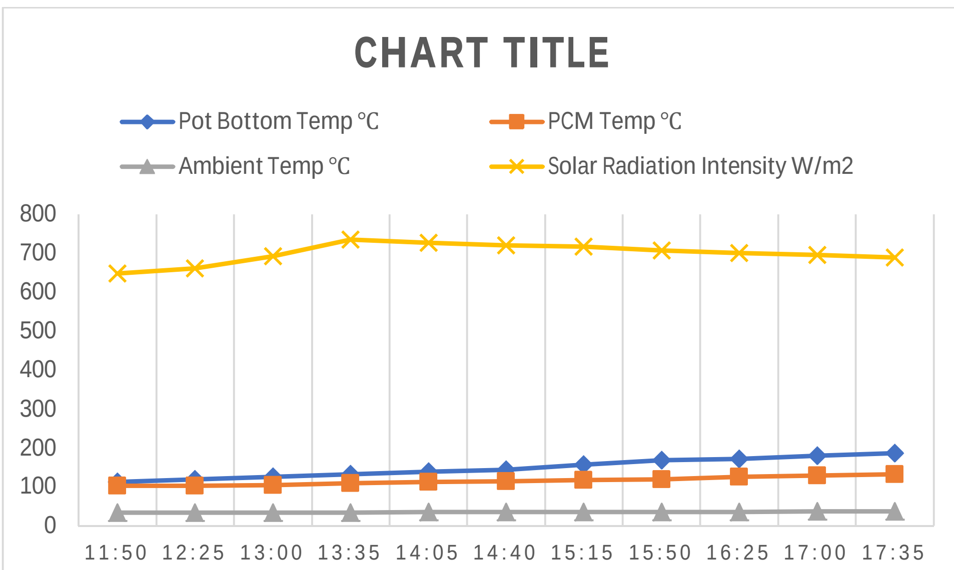


Graph 10 : Variation of temperature of thermal energy storage, cooking medium and solar radiation intensity with time.

3) PCM Charging again Charging time 5 hrs

In order to charge the PCM for the second round of cooking, the solar cooker was once more exposed to sun radiation. This time, PCM charging was left running until 17:35 hours to allow for PCM superheating. The temperature outside is between 33.1°C and 36.3°C. PCM temperature increases from 102°C to 132°C. Due to clouds, solar radiation changes during the charging process from 690 W/m2 to 649 W/m2. A reading was obtained every 35 minutes.

Time	Pot Bottom Temp °C	PCM Temp °C	Ambient Temp °C	Solar Radiation Intensity W/m^2
11:50	112	102	33.1	649
12:25	119	103	33.4	661
13:00	125	105	33.9	692
13:35	133	109	34.4	735
14:05	139	112	34.8	727
14:40	144	115	35	721
15:15	157	118	35.3	717
15:50	168	119	35.5	707
16:25	172	125	35.9	701
17:00	180	129	36.7	696
17:35	186	132	36.3	690

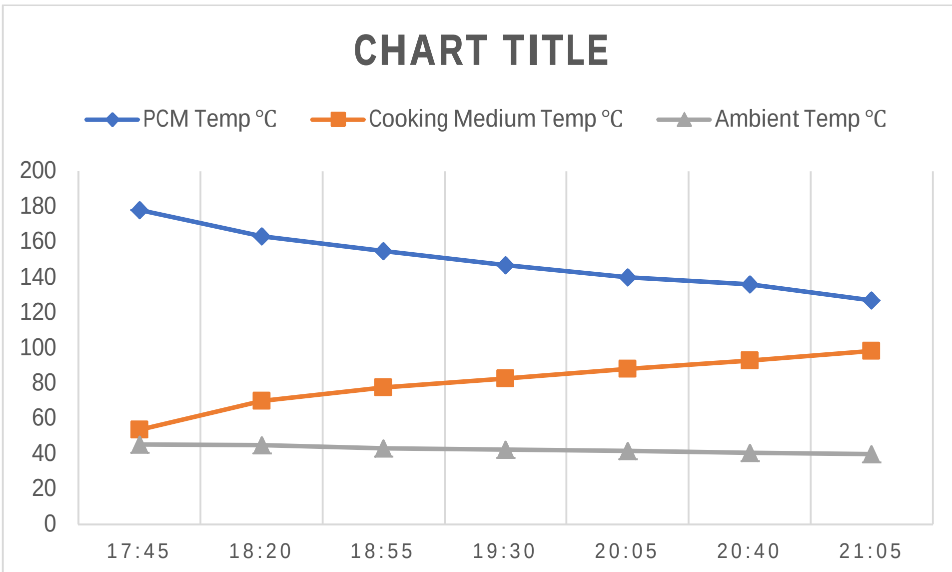


Graph 11 : Variation of temperature of thermal energy storage and solar radiation intensity with time

4) PCM Discharging with food time 3hrs not cooked well

Superheated PCM within a solar cooker pot that has been raised from a parabolic dish collection plate and placed inside a wooden insulation box that has been lined with thermocol sheets to boost the efficiency of the cooker. 420 gallons of water and 210 grammes of rice are placed in the solar cooker pot. As time goes on, the PCM temperature drops to 127°C as a result of heat transfer from the PCM to the cooking medium. Cooking medium temperature now reaches 64°C. Rice was not properly cooked at 21:05 hours PCM temperature of 78°C and cooking medium temperature of 98.2°C. There were readings collected every 35 minutes.

Time	PCM Temp °C	Cooking Medium Temp °C	Ambient Temp °C
17:45	178	53.4	45.3
18:20	163	69.9	44.7
18:55	155	77.5	42.9
19:30	147	82.7	42.4
20:05	140	88.2	41.7
20:40	136	92.6	40.6
21:05	127	98.2	39.7



Graph 12 : Variation of temperature of thermal energy storage and cooking medium with time

5) Stagnation Temperature test

Test air with a stagnation temperature is employed as the working medium. Digital thermocouples are used to determine the temperature of the air within the pot. First, this test was conducted without utilizing any heat energy storage devices, and then it was conducted again using these devices: neopentyl glycol, paraffin wax, and the high temperature PCM known as therminol VP-1. In the first scenario, air temperature begins to climb at 25.3°C and initially rises more quickly. After some time, however, temperature rises steadily until it reaches 81.2°C. Later, a thermal energy storage system (PCM) is employed, and throughout this test, the air temperature within the device ranges from 26.4°C to 84.3°C. Additionally, using Paraffin Wax to store thermal energy, the Air temperature ranges from 27.1°C to 87.4°C. Fig.-

Time	Air Temperature °C		
	Neopentyl giycol	Paraffin wax (e.g.octadecane)	Therminol VP-1(hight temperature pcm)
09:00	25.3	26.4	27.1
09:20	46	43	45.2
09:40	55.5	55.5	57.9
10:00	60.7	62.7	64.2
10:20	67.4	70.9	74.5
10:40	75.3	75.7	81.8
11:00	81.2	84.3	87.4

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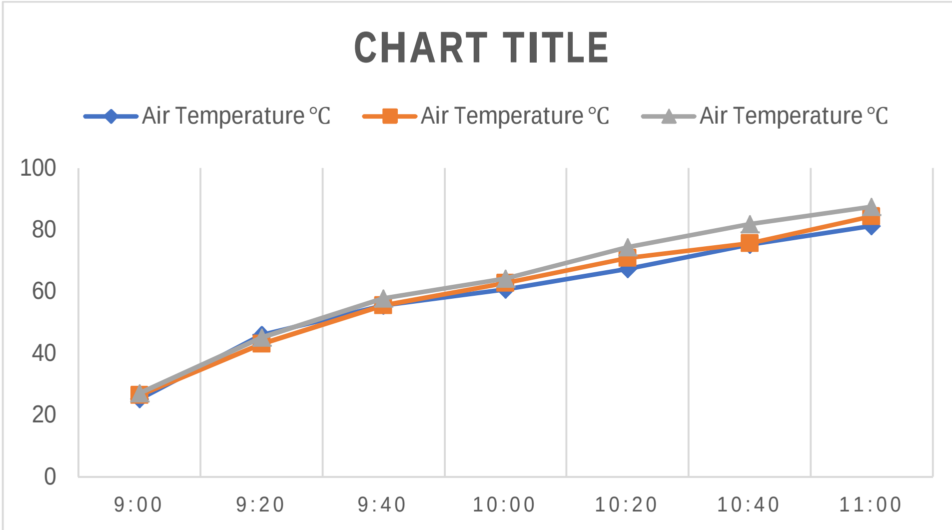
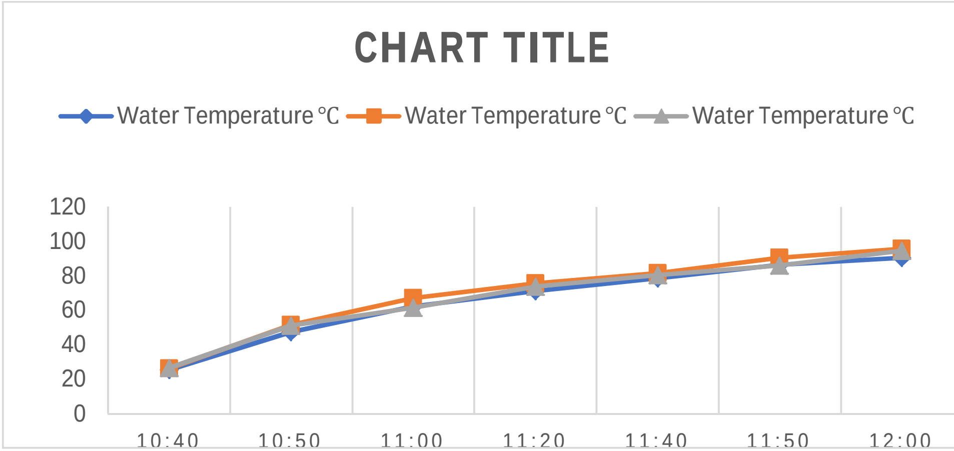


Graph 13 : Variation of air temperature inside the pot with time

6) Water Heating Test

The pot with 1000 ml of water was placed on the focal point of the parabolic dish collector. Without a thermal energy storage device, the water temperature in the first scenario rises from 25.4°C to 90.5°C. In a different scenario, a thermal energy storage system causes the water temperature to rise from 26.4°C to 95.8°C and from 26.5°C to 94.7°C when is used as the PCM. The heat energy storage device, which functions as an energy reservoir and an insulator so that heat loss to the surroundings is greatly reduced, is what causes the difference in the water temperature in each example. Fig.-

Time	Water Temperature °C		
	Neopentyl giycol	Paraffin wax (e.g. Octadecane)	Therminol VP-1(hight temperature PCM)
10:40	25.4	26.4	26.5
10:50	47.6	51.6	51.1
11:00	62.2	67.1	61.7
11:20	71.1	75.8	73.8
11:40	78.8	81.7	80.6
11:50	86.4	90.7	86.1
12:00	90.5	95.8	94.7

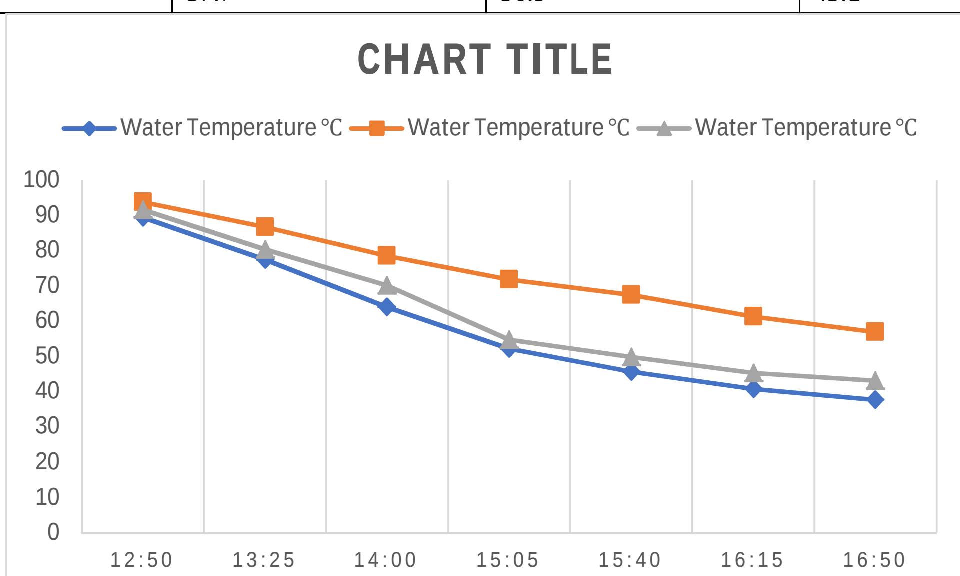


Graph 14 : Variation of water temperature inside the pot during heating test with time

7) Cooling Test

The experimental setup is covered with a large umbrella once the water has been heated to a specific degree and the temperature of the water begins to drop. Without a thermal energy storage device, the water temperature in the first scenario lowers more quickly than in the other one and goes from 89.3°C to 37.7°C in 90 minutes. In a subsequent scenario, erythritol, a thermal energy storage device, causes the water temperature to progressively decline, going from 93.8°C to 56.9°C, and PCM , from 91.5°C to 43.1°C. Fig.-

Time	Water Temperature °C		
	Neopentyl giycol	Paraffin wax (e.g. Octadecane)	Therminol VP-1(hight temperature PCM)
12:50	89.3	93.8	91.5
13:25	77.4	86.7	80.4
14:00	63.9	78.5	70.2
15:05	52.2	71.8	54.8
15:40	45.6	67.4	49.9
16:15	40.8	61.3	45.2
16:50	37.7	56.9	43.1



Graph 15 : Variation of water temperature inside the pot during cooling test with time

IV. CONCLUSION

A. *Stagnation Temperature test*

stagnation temperature tests conducted on Neopentyl glycol, paraffin wax (octadecane), and Therminol VP-1 (a high-temperature phase change material or PCM) within the solar collector yielded valuable insights. As the exposure duration increased, the stagnation temperatures consistently rose for all three PCMs, showcasing their capacity to store thermal energy during stagnation periods.

B. *Water Heating test Time*

The distinctive temperature behaviors emphasize the importance of selecting an appropriate PCM tailored to specific temperature requirements. Neopentyl glycol and paraffin wax are suitable for moderate-temperature applications, while Therminol VP-1 excels in high-temperature solar thermal systems.

The water heating tests provided valuable insights into the thermal performance of Neopentyl glycol, paraffin wax (octadecane), and Therminol VP-1 (a high-temperature phase change material or PCM) for heating water. As the exposure duration increased, all three PCMs effectively transferred thermal energy to the water, elevating its temperature.

Therminol VP-1 showcased efficient heating capabilities, raising the water temperature to 94.7°C by 12:00. Paraffin wax closely followed, achieving a temperature of 95.8°C. Neopentyl glycol exhibited slightly lower temperatures, reaching 90.5°C by 12:00.

C. *Cooling Test*

The cooling tests provided insights into the thermal performance of Neopentyl glycol, paraffin wax (octadecane), and Therminol VP-1 (a high-temperature phase change material or PCM) for cooling water. As the exposure duration increased, all three PCMs effectively absorbed thermal energy from the water, leading to a decrease in temperature.

Therminol VP-1 exhibited efficient cooling capabilities, with the water temperature reaching 43.1°C by 16:50. Paraffin wax closely followed, achieving a temperature of 56.9°C. Neopentyl glycol exhibited slightly higher temperatures, reaching 37.7°C by 16:50.

V. FUTURE SCOPE

1) This study sets the stage for future research in various directions. Further investigation into a wider range of PCMs, including novel PCM composites, would enhance the understanding of their suitability for water heating applications. Exploring advanced encapsulation techniques and integration of PCMs into water heating systems for real-world applications are crucial steps. Additionally, assessing the long-term stability and cyclic performance of PCMs is essential for sustainable and reliable utilization. The findings from this study can guide the development of efficient PCM-based water heating systems, contributing to energy conservation and sustainable heating solutions.
2) This study sets the stage for future research in various directions. Further investigation into a wider range of PCMs, including novel PCM composites, would enhance the understanding of their suitability for water heating applications. Exploring advanced encapsulation techniques and integration of PCMs into water heating systems for real-world applications are crucial steps. Additionally, assessing the long-term stability and cyclic performance of PCMs is essential for sustainable and reliable utilization. The findings from this study can guide the development of efficient PCM-based water heating systems, contributing to energy conservation and sustainable heating solutions.
3) This study paves the way for future research in several directions. Further investigation into a broader spectrum of PCMs and varied environmental conditions will enhance our understanding of PCM behavior during cooling processes. Exploring innovative encapsulation techniques to improve thermal conductivity and stability of PCMs is essential. Additionally, studying the impact of different cooling rates and examining the cyclic stability of PCMs for prolonged use will contribute to practical applications. Integration of PCMs into cooling systems, such as air conditioning, can also be explored for potential energy-efficient cooling solutions. Overall, the findings lay the groundwork for utilizing PCMs in cooling applications, promoting sustainable and efficient cooling technologies.

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