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Experimental Investigation of Heat Transfer Coefficient in Parabolic Dish Solar Cooker with Thermal Energy Storage System

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Abstract: The use of solar cooking can help cut back on the consumption of fossil fuels. Due to the rising expense of fossil fuels, there is a great demand for an energy efficient and affordable solar cooking technology, and it is currently the most popular study topic worldwide. This study examines how a thermal energy storage material (Erythritol) can improve the thermal performance of solar parabolic dish cookers. On the cooking vessel with and without thermal energy storage material, tests for stagnation temperature and water boiling and cooling are performed. In terms of thermal performance, heat loss factor, optical efficiency experimental results for the two instances are analysed. Heat loss factor was found to be 16.8 W/m²K and 28.21 W/m²K in with and without thermal energy storage system.

Keywords: Parabolic Dish solar cooker, Thermal energy storage material, Heat transfer coefficient

Nomenclature

$\dot{Q}$	Heat loss rate from pot, W
A_t	Surface area of pot, m^2
F	Heat exchange efficiency factor
T_a	Ambient air temperature, K
U_L	Overall heat loss factor of pot, W/m^{2}K
T_W	Water temperature inside pot, K
$(MC)_W$	Heat capacity of water, J/K
τ	Time, s
$\dot{Q}_u$	Useful heat absorption rate by water, W
η_o	Optical efficiency
I_b	Solar beam irradiation on the plane of aperture
A_p	Aperture area, m^2

I. INTRODUCTION

Solar energy is becoming an increasingly necessary and viable solution for cooking in today's world. As the world's population keep expanding, the demand for cooking fuel also rises. Traditional cooking methods, such as burning wood or fossil fuels, contribute to deforestation, air pollution, and greenhouse gas emissions, and impacting human health. In this context, solar energy offers a sustainable and clean alternative. The necessity of solar energy for cooking is multi-fold. Firstly, it reduces reliance on non-renewable energy sources, mitigating the depletion of fossil fuels and lowering greenhouse gas emissions. By adopting solar cooking methods, households and communities can significantly contribute to combating climate change and transitioning towards a sustainable energy future. Moreover, solar cooking is an invaluable tool in areas with limited access to electricity and cooking fuels. In rural and remote regions, where infrastructure development is challenging, solar cookers offer an affordable and accessible solution. They provide a reliable source of energy for cooking, reducing the need for long-distance fuel transportation and the associated costs. Solar energy is a necessary and transformative solution for cooking. It addresses the pressing issues of climate change, environmental degradation, and public health concerns caused by traditional cooking methods.

By harnessing the power of the sun, solar cookers offer a sustainable, clean, and accessible alternative that can improve the life quality for individuals and communities worldwide.

There are various types of solar cookers designed to harness the power of sunlight for cooking. One common type is the box type solar cooker, also known as a solar box cooker. It is made out of an insulated box with a transparent lid or cover, which allows sunlight to enter and traps the heat inside. The inner walls of the box are often black or lined with reflective material to absorb and retain heat. Food is placed in pots or containers inside the box, and the solar energy slowly cooks the food over time.

Another type is the panel-type solar cooker, which typically consists of multiple reflective panels arranged in a box-like structure. These panels reflect and concentrate sunlight onto a central cooking area, where pots or trays are placed. Panel-type solar cookers are often lightweight, portable, and relatively simple in design, making them suitable for outdoor activities and camping. A third type is the parabolic dish solar cooker, which features a concave, reflective dish that concentrates sunlight onto a focal point.

Additionally, there are hybrid solar cookers that combine solar power with other energy sources. For example, some hybrid models include the option to use electric or gas heating elements as a backup for cloudy days or when additional cooking power is needed.

The parabolic dish solar cooker offers several advantages over the box type solar cooker, making it a preferred choice for certain cooking applications. One significant advantage is its higher cooking temperature potential. The parabolic dish design concentrates sunlight onto a focal point, resulting in intense heat generation. This concentrated heat allows for faster cooking times and the ability to perform tasks such as frying and grilling, which require higher temperatures than what a box type solar cooker can achieve. Another advantage is the ability of the parabolic dish solar cooker to track the sun's movement throughout the day. The parabolic shape of the dish allows it to be easily adjusted to face the sun, maximizing the amount of sunlight captured. This feature ensures that the cooker operates at its maximum efficiency, optimizing the cooking process even during periods of less direct sunlight, such as early morning or late afternoon.

Solar cookers, while offering many benefits, do have certain limitations that should be considered. One significant limitation is their dependence on sunlight. Solar cookers rely on direct sunlight to generate heat, which means they may not be suitable for use in areas with frequent cloud cover or limited sunlight. In such regions or during periods of inclement weather, the cooking efficiency of solar cookers can be significantly reduced, making them less reliable compared to traditional cooking methods. Another limitation is their cooking time. Solar cookers generally take longer to cook food compared to conventional stoves or ovens. Solar cooking is a slower process as it relies on the gradual accumulation of solar heat. This longer cooking time can be a challenge when there are time constraints or a need for quick meal preparation.

To overcome above problems thermal energy storage system can be used in solar cooker. A solar cooker with thermal energy storage is an advanced type of solar cooker that incorporates a mechanism to store excess heat energy generated by the sun. This stored thermal energy can then be utilized for cooking during periods of reduced or no sunlight availability. The addition of thermal energy storage addresses one of the limitations of traditional solar cookers, which heavily rely on direct sunlight for cooking and cooking time.

Lokeswaran S. et al.[1] experimented the solar parabolic dish cooker with porous medium like waste metal chips from various machining process . And they find out a reasonable increase in cooker efficiency from 23% to 34%.

Mullick S.C. et al. [2]prepare a test for paraboloid concentrator solar cooker, in which they found out that time required to boil water for any given condition of ambient temperature and solar beam insolation can be calculated by performance curve.

A box-style solar cooker was created by Buddhi et al.[3] using phase change material(commercial-grade stearic acid) to store heat energy during the day and use it for cooking during the hours of low sunlight. They learned that food can be cooked in a solar cooker with latent heat storage even when there isn't any sunshine.

Reddy et al.[4] used COSMOL software to optimise the gap between the trays that house PCM (Paraffin wax) and compare the solar cookers with and without thermal energy storage systems. They discovered that the solar cooker with PCM was able to maintain a temperature up to 17°C higher at 6:30 pm.

Yadav et al.[5] did evaluation of the parabolic dish collector type solar cooker's thermal efficiency uses commercial grade acetamide as a phase transition material in conjunction with various sensible heat storage materials, including sand, iron gris, stone pebbles, and iron balls. They found that the PCM-Stone pebble and PCM-Sand combination stores heat three to five times more effectively than the PCM-Iron grits and PCM-Iron ball combo. While the exterior surface (sensible heat storage materials) aids in maintaining PCM temperature, the PCM is primarily responsible for cooking meals.

Senthil R [6] investigated the effectiveness of a parabolic dish solar cooker using paraffin wax as a thermal energy storage medium and concentric cylinders as the vessel. The variables under research were heat loss, cooking power, cooking time, and required heat. He discovered that it took 90 minutes with PCM and 120 minutes without PCM to reach water at 90°C.

The energy and exergy efficiency of the box type and parabolic dish solar cookers are compared by Rathore N et al. in [7]. According to the results of the trial, the parabolic dish solar cooker generated more energy and exergy than the box solar cooker.

Tanzanian researcher Rulazi E.A. [8] investigated the thermal efficiency of solar cookers. When tested, the average maximum temperature for water, meat, and beans was 121°C. It took 15 minutes, 50 minutes, and 90 minutes to cook the beans, meat, and water, respectively.

The box-type solar cooker is studied by Palanikumar G et al. [9] employing flexible thermography and nanocomposite as the phase-change material. The proposed cooker that is integrated with NPCM was evaluated for performance using Cramer's rules, fuzzy logic, and image processing techniques. The bar plate absorber temperature for the solar box type cooker with NPCM, PCM, and without NPCM was achieved at 163°C, 147°C, and 113.34°C, respectively, under the 1037 W/m^2 of solar radiation intensity.

The receiver design for solar cooking utilising a parabolic dish was improved by Theu A.P. et al.[10] As an alternative to the traditional receiver system, insulated (IR), air-filled (AFR), and oil-filled (OFR) receivers were tested. According to the study, performance improved when the IR system was employed instead of the AFR and OCR systems.

Sunflower oil and Roki oil were researched for their thermo-physical characteristics and capacity for thermal energy storage by Abedigamba O.P. et al. [11]. Roki oil reached a higher temperature during the charging period than sunflower oil. It was discovered that Roki oil had a greater heat utilisation temperature than sunflower oil.

In order to examine the performance of a solar cooker, Tawfik M.A. et al. [12] employed paraffin wax as a thermal energy storage medium and a bottom parabolic reflector with tracking system (TBPR) with a newly created absorber plate. In the study, it was discovered that solar cookers with TBPR reached the necessary cooking temperature 15-20 minutes earlier than solar cookers without TBPR.

II. METHODS AND MATERIALS

A. Solar Parabolic Dish Collector

A solar parabolic dish collector is a device designed to concentrate sunlight onto a focal point using a parabolic-shaped dish. It is primarily used for harnessing solar energy to generate high temperatures for cooking, heating, or even power generation. The parabolic dish collector consists of a reflective surface made of aluminium sheets. This shape allows the collector to focus incoming sunlight onto a single focal point. The reflective surface of the parabolic dish is designed to redirect and concentrate sunlight onto the focal point. This concentration of sunlight results in a highly intense heat at the focal point, significantly higher than ambient temperatures. To ensure that the bottom of the cooking utensil is continuously exposed to the concentrated solar radiation, a manual tracking mechanism is employed to adjust the dish's axis orientation so that it is parallel to the sun's rays. Tracking is done at interval of 15 min.Solar parabolic dish collector used in experiment is shown in Fig. 1

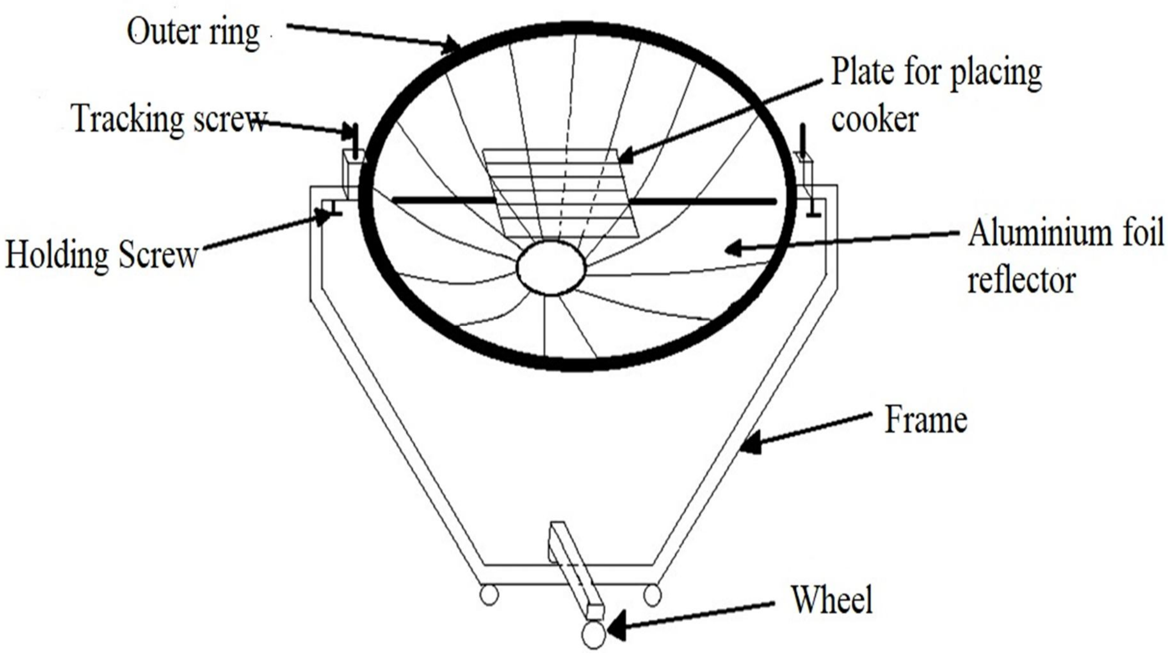

Fig. 1 Schematic diagram of parabolic dish collector

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Table-1 Technical description of parabolic dish concentrator

S.No.	Particulars	Specification
1	Aperture diameter	1.4 m
2	Depth of parabolic	0.38 m
3	Focal length	0.322 m
4	Surface area	1.93 m^2

B. *Thermal Energy Storage System*

In experimental setup sugar alcohol (Erythritol $C_4H_{10}O_4$) is used as thermal energy storage system to store the solar radiation energy in heat form. Erythritol is a sugar alcohol that is commonly used as a low-calorie sweetener. It occurs naturally in some fruits and fermented foods, but the erythritol used commercially is typically produced by fermenting glucose or cornstarch.

The thermophysical properties of Erythritol [13] is given in the table 2.

Table 2: Thermophysical properties of Erythritol

Material	Melting Point(°C)	Specific heat ($KJKg^{-1}K^{-1}$)	Latent Heat ($KJKg^{-1}$)	Density (kgm^{-3})	Thermal conductivity ($Wm^{-1}K^{-1}$)
Erythritol	118	1.68	340	1450	0.73

Fig. 2 Photograph of Erythritol sugar alcohol powder

C. *Measuring Instruments*

Instruments used in experiment are discussed in table 3.

Table – 3: Measuring Instruments with their accuracy

Device	Measured Parameter	Accuracy	Range
Pyranometer	Global Radiation	± 5%	0-4000 W/m^2
Thermocouple	Temperature	± 0.2% ℃	0-200 ℃
Measuring Tape	Length	± 1 %	0-5 m
Weighing Machine	Weight	± 1 %	0-30 Kg

III. EXPERIMENTAL PROCEDURE

The arrangement is adjusted, the cooking item is kept in the centre, and the parabolic dish's axis is aligned with sun radiation. The bottom surface of the utensil receives focused sun energy from the reflector. The walls of the utensil distribute the heat to the grains as they cook. In order to continually expose the receiver surface to the focused solar light, manual tracking is performed every 15 minutes.

From the appropriate measurement devices, the receiver plate temperature, water temperature, and solar insolation are registered. One thermocouple is placed in the centre of the cooker, while the other is placed at the base of the receiving plate, to measure the temperature.

To evaluate the thermal performance of parabolic dish collector type solar cooker with and without thermal energy storage system experiment were done in the month of April 2023.

A. Stagnation Temperature Test

The measurement of the maximum air temperature is the goal of this test. Air is used as the working medium for this. By placing the solar cooker in the solar parabolic dish's concentrating region, it was exposed to sunlight both with and without the thermal energy storage material. At intervals of 15 minutes for both cases, the ambient temperature, the air temperature within the cooker, and solar radiation were measured.

B. Water Heating Test

This test was carried out to evaluate thermal performance of solar cooker. 1000 mL of water in a cooker were used for this test. The cooker is positioned so that, with its aperture fixed at normal to the sun, the concentrator gets the maximum quantity of incoming solar energy. The solar cooker pot with black coating was placed at the solar parabolic dish's focal point. For both with and without heat energy storage arrangement, the water temperature progressively rises at the beginning of the experiment. The experiments went on until the water reached a temperature above boiling. Then the heating is stopped.

C. Cooling Test

The main objective of this test is to evaluate the heat loss factor by covering the solar cooker under investigation with a big picnic umbrella after the heating test.

IV. MATHEMATICAL ANALYSIS

A. Heat Loss Factor In Cooling Test

For a small time duration during cooling of water in sensible cooling zone, the time taken $d\tau$, for temperature difference dT_W of water is –

$$d\tau = -\frac{(MC)_w dT_w}{\dot{Q}_L} = -\frac{(MC)_w dT_w}{A_t F U_L (T_w - T_a)} \quad (1)$$

Considering ambient temperature T_a and overall heat loss factor U_L constant during water cooling test, integrate equation (1) over small time duration τ, temperature of water drops from T_{wo} to T_w during this period.

$$\tau = -\tau_O \frac{(MC)_w}{A_t F U_L} \ln\left[\frac{(T_w - T_a)}{(T_{wo} - T_a)}\right] \quad (2)$$

Equation (2) can be rewritten as-

$$(T_w - T_a) = (T_{wo} - T_a) e^{-\tau/\tau_o} \quad (3)$$

Where $\tau_o = \frac{(MC)_w}{A_t F U_L}$ (4)

B. Optical Efficiency Factor In Heating Test

During sensible heating of water inside the pot, time taken $d\tau$ to rise infinitesimal water temperature dT_w –

$$d\tau = \frac{(MC)_w dT_w}{\dot{Q}_u} = \frac{(MC)_w dT_w}{F[A_p \eta_o I_b - A_t U_L (T_w - T_a)]} \quad (5)$$

Considering solar insolation and ambient temperature to be constant for a certain time interval, if the temperature of water changes from T_{w1} to T_{w2} so after integrating-

$$\tau = -\tau_o \ln\left[\frac{F\eta_o - \frac{FU_L}{C}\left(\frac{T_{w2} - T_a}{I_b}\right)}{F\eta_o - \frac{FU_L}{C}\left(\frac{T_{w1} - T_a}{I_b}\right)}\right] \quad (6)$$

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Where $C = \frac{A_p}{A_t}$

From equation (6) we can find optical efficiency factor $F\eta_o$ as –

$$F\eta_o = \left(\frac{FU_L}{C}\right)\left[\frac{\left(\frac{T_{w2}-T_a}{I_b}\right)-\left(\frac{T_{w1}-T_a}{I_b}\right)e^{-\tau/\tau_o}}{1-e^{-\tau/\tau_o}}\right] \quad (7)$$

V. RESULT AND DISCUSSION

A. *Stagnation Temperature Test*

In stagnation temperature test air is used as working medium. Temperature of air inside the pot is measured using a digital thermocouple. Firstly this test was performed without using any heat energy storage arrangement and after that again test is performed using heat energy storage arrangement. In the first case temperature of air starts rising from 38.4°C and initially it rises at faster speed and after some time temperature rises gradually and finally goes up to 85.1°C. In later case a thermal energy storage system (Erythritol) is used and in this test temperature of air inside the starts from 37°C and goes up to 89.1°C. Fig.-3

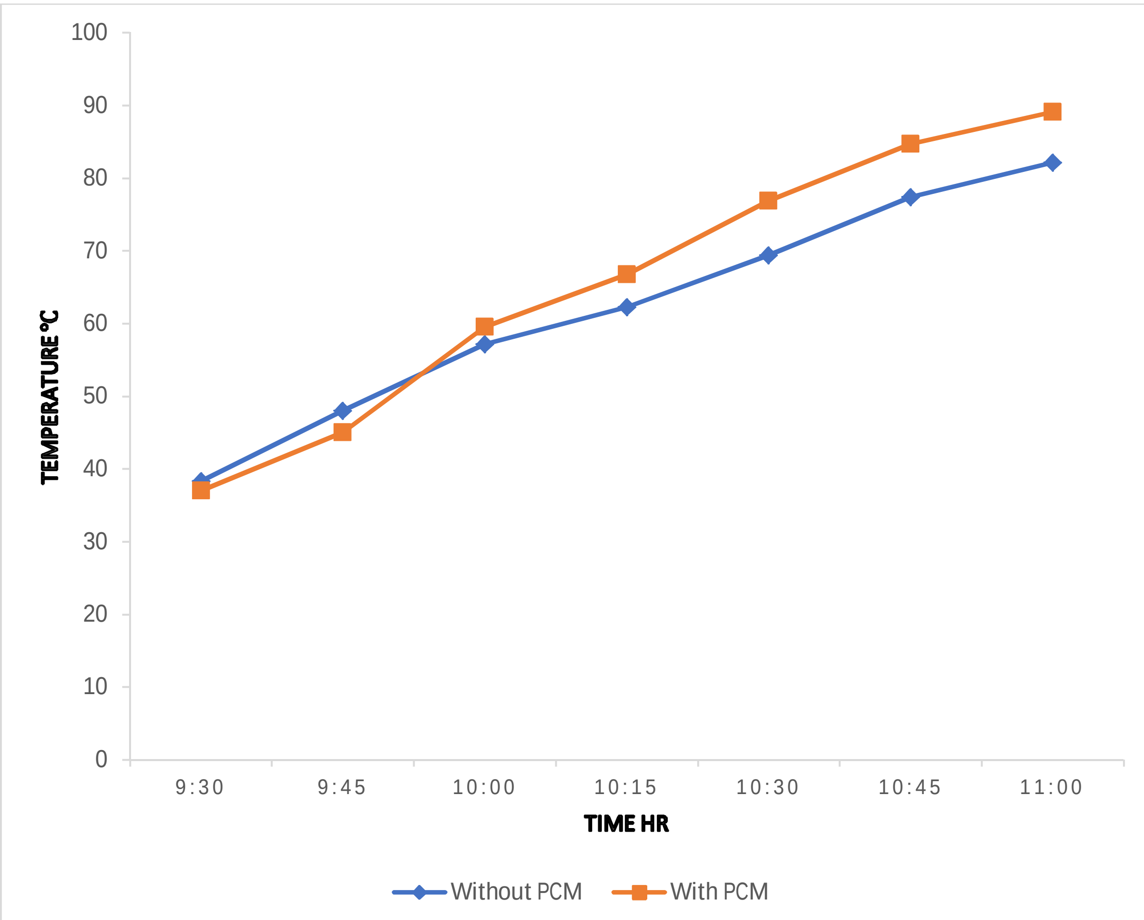

Fig.- 3 Variation of air temperature inside the pot with time

B. *Water Heating Test*

1000 ml of water was put inside the pot and placed on the parabolic dish collector's focal point. In first case i.e. without heat energy storage system water temperature starts rising from 36.3°C and goes up to 93.5°C. In another case i.e. with heat energy storage system water temperature goes from 36.5°C to 98.8°C. The difference in the water temperature in both the cases is due to the heat energy storage system which works as energy reservoir as well as insulator due to which heat loss to the surrounding minimizes to a great extent. Fig.- 4

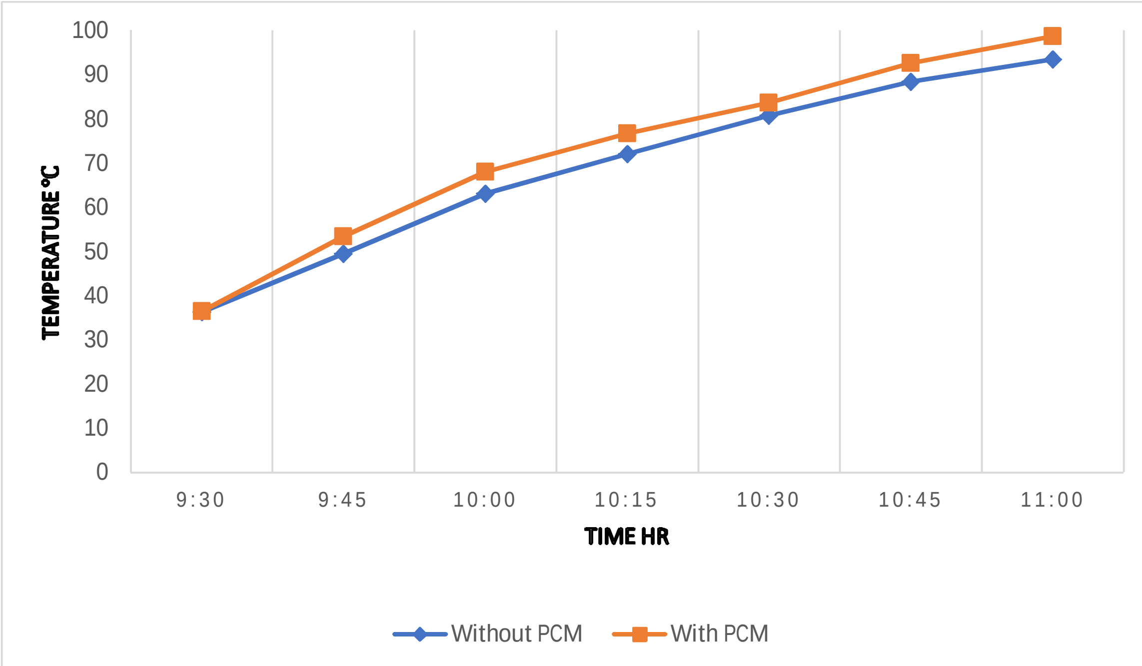

Fig.- 4 Variation of water temperature inside the pot during heating test with time

C. Cooling Test

After heating water up to a certain point experimental setup is covered under a big umbrella and temperature of water starts decreasing. In first case i.e. without thermal energy storage system water temperature decreases at faster rate as compared to other one and temperature drops from 90.3℃ to 39.7℃ in 90 minutes. In later case water temperature drops gradually due to thermal energy storage system and it goes from 95.7℃ to 58.9℃. Difference in the water temperature increases as the time passes. Fig.- 5

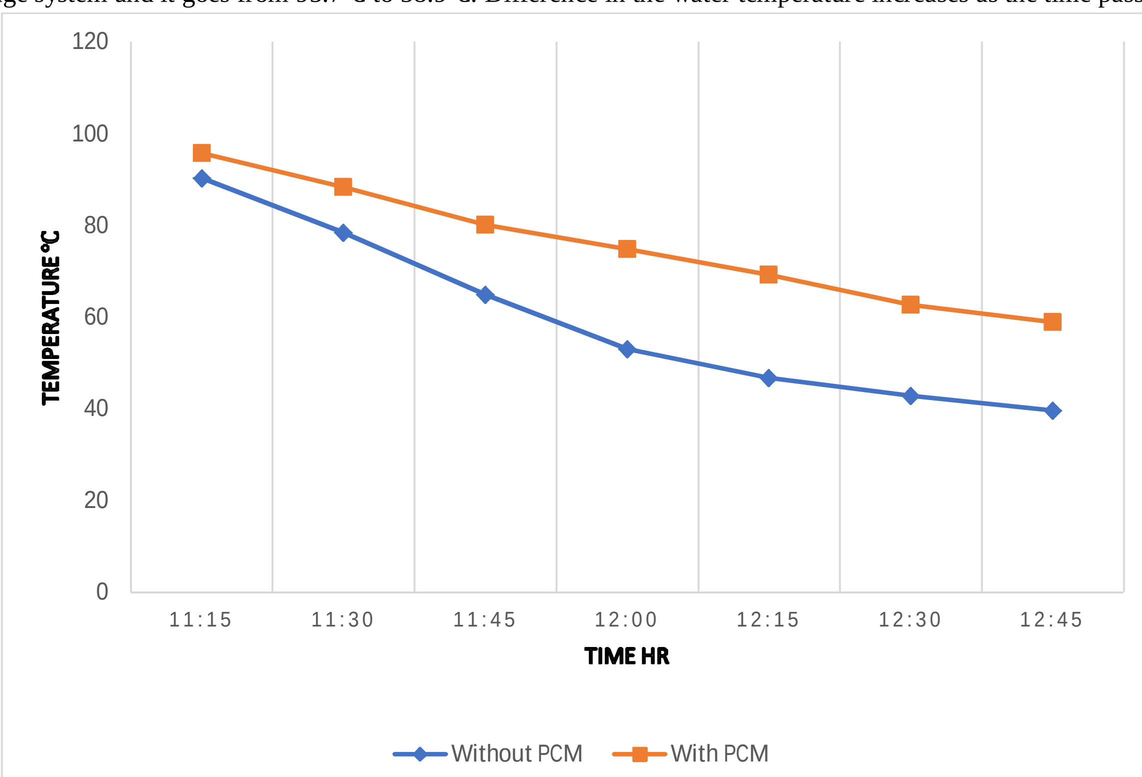

Fig.- 5 Variation of water temperature inside the pot during cooling test with time

D. Heat Loss Factor In Cooling Test

Using equation (2) heat loss factor (FU_L) can be find out in both the cases i.e. without heat energy storage arrangement and with heat energy storage arrangement. By calculation heat loss factor in without heat energy storage arrangement found to be 28.21 W/m^2K. And in with heat energy storage arrangement heat loss factor found to be 16.8 W/m^2K. The difference in heat loss factor shows that in later case rate of heat loss is less as compared to first case and due to which water temperature inside the pot decreases slowly in cooling test and remain warm for long time. The reason of difference in heat loss factor is due to placement of thermal energy storage system which act as a resistance to heat flow towards the surrounding.

E. Optical Efficiency Factor In Heating Test

Using equation (7) optical efficiency factor $(F\eta_o)$ in heating test is find out to be 0.186 in without heat energy storage arrangement and 0.221 in with heat energy storage arrangement. Higher value of optical efficiency factor in later case is due to energy stored in Erythritol.

VI. CONCLUSIONS

Experimental testing of the parabolic dish solar cooker was done both with and without thermal energy storage system. The stagnation temperature was found out 7℃ more in case of with thermal energy storage system. In Cooling test and heating test this difference was approximately 19℃ and 6℃ respectively. Heat loss factor was calculated 16.8 W/m^2K and 28.21 W/m^2K for with and without heat energy storage arrangement respectively. Optical efficiency factor calculated 0.221 and 0.186 for with and without heat energy storage arrangement respectively. Overall conclusion from above experiment can be concluded as deployment of thermal energy storage system in parabolic dish solar cooker can improve the performance and efficiency of solar cooker.

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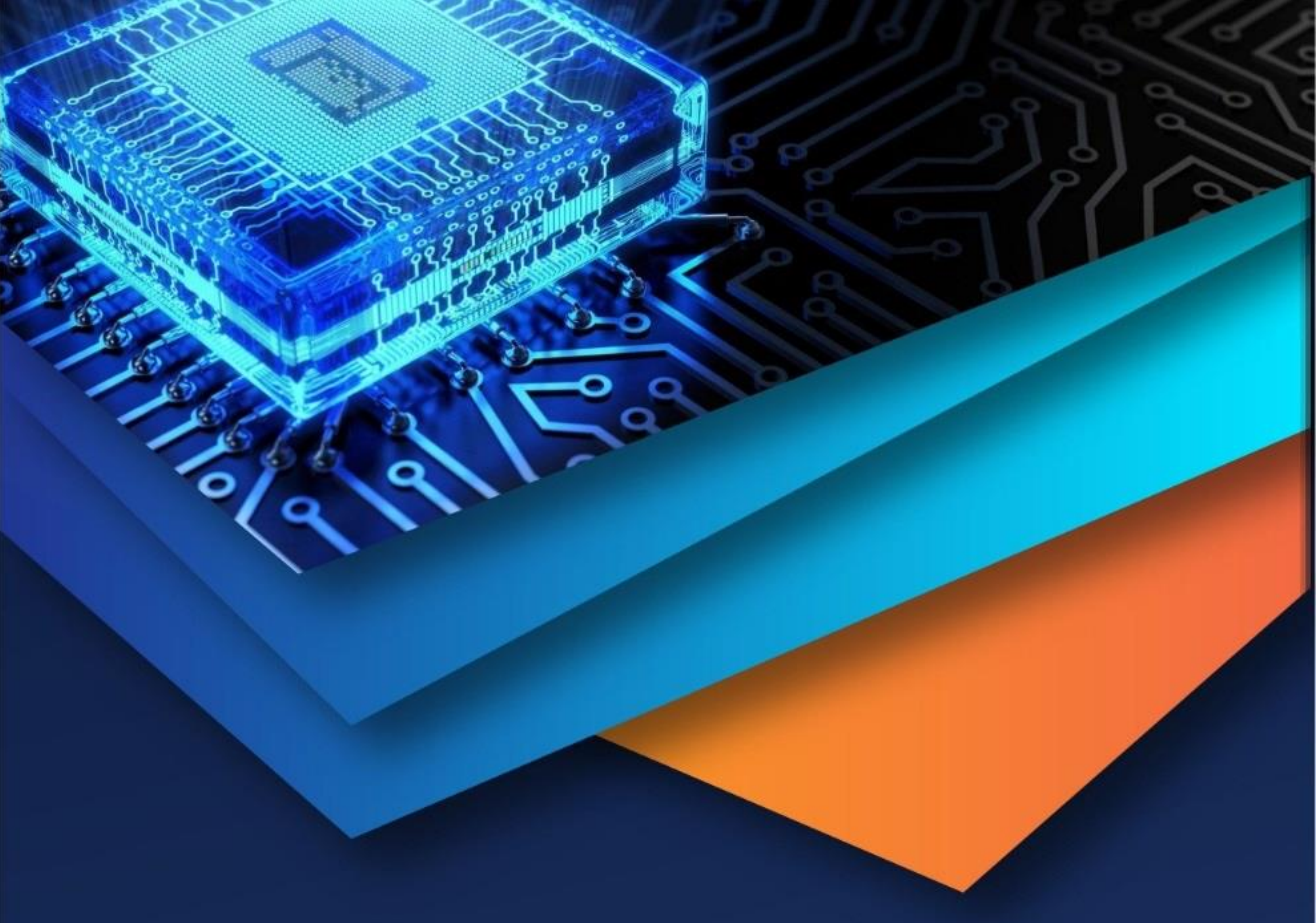

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