Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000873

Research Article

Experimental investigation to evaluate thermal performance of a solar cooker with evacuated tube solar collector using different heat transfer fluids

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ARTICLE INFO

Article history
Received: 03 August 2023
Revised: 19 December 2023
Accepted: 11 January 2024

Keywords:
Evacuated Tube Solar Collector; Heat Transfer Fluid; Phase Change Material; Solar Cooker; Thermal Performance

ABSTRACT

In present research the impact of insulation on the discharge process of phase change material (PCM) and a comparison of the thermal performance of a solar cooker using two distinct types of heat transfer fluid (HTF) were experimentally investigated. The aim of this study is to select best performing HTF at the thermal performance point of view. In this experiment a solar cooker with an integrated PCM thermal storage unit was connected through connecting pipes to an evacuated tube solar collector. Separately, water and SigmaTherm−K were used as HTF to evaluate the thermal performance of a solar cooker. Acetanilide of commercial grade was utilized as thermal storage material in the solar cooker. Both charging and discharging of PCM were studied with insulation and without insulation. It was discovered that the temperature attained with PCM in an insulated cooker is 16.5°C and 19.3°C higher than without PCM using water and SigmaTherm−K as HTF respectively. It was concluded that using PCM with the SigmaTherm−K increased the amount of average energy by 29.11% compared to water. The temperature attained by water as cooking load increased from 22°C to 77°C and from 20.1°C to 86.2°C using water and SigmaTherm−K as a HTF respectively.

Cite this article as: Khan Y, Tevatia A, Apparao D, Singh N, Mishra S. Experimental investigation to evaluate thermal performance of a solar cooker with evacuated tube solar collector using different heat transfer fluids. J Ther Eng 2024;10(5):1335−1346.

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This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

INTRODUCTION

The importance of solar energy lies in its abundant availability and its role in mitigating climate change. Solar energy is abundantly available, as it harnesses the power of the sun, which radiates immense amounts of energy every day. Moreover, its clean and renewable nature makes it a vital tool in reducing greenhouse gas emissions and transitioning towards a more sustainable energy future [1]. The production of electricity in today's world necessitates a careful consideration of two critical factors: the escalating demand for energy and the imperative of incorporating renewable energy sources to promote sustainable development. The array of renewable energy sources encompasses hydroelectric power, solar energy, wind power, geothermal energy, and numerous other sustainable options [2, 3]. The use of the solar energy is very essential due to the abundantly available, and noise free operation. Nowadays solar energy plays very important part providing the clean and zero emission energy [4]. However, present research considers the solar cooker analysis due to its extensive benefit to the environment such as no emission and lower cost etc [5, 6].

The use of PCM with evacuated tube solar thermal collectors was reported by authors Aramesh and Shabani [7]. Their research indicates that evacuated tube solar collector (ETSC)-PCM technology needs continual advancements. To reduce the need of auxiliary heaters, they emphasized the necessity for techno-economic feasibility studies and more effective designs. The authors also emphasized the value of comparing performance evaluations of various PCMs while creating a selection manual to enhance ETSC-PCM systems. Olfian et al. [8] investigated the thermal performance of an ETSC integrated with PCM. Their primary objective was to analyze the functionality of a U-type ETSC that utilizes PCM to store excess daytime solar energy for nocturnal use. The focal points of their study included the maintenance of a consistent outlet temperature of approximately 40°C during daylight hours. Their findings indicated that the 6 mm diameter tube exhibited significant enhancements, including a 25% improvement in liquid fraction and a 13.5% increase in fluid outlet temperature at 3:00 PM during charging when compared to other diameters. Yang et al. [9] conducted a comparative study between the integrated PCM into an ETSC and a novel renewable-based unit comprising of an ETSC, photovoltaic module, PCM, and porous metal foam. The unit with all components showed the highest energy efficiency, outperforming a conventional collector by 13%. Factors like PCM melting temperature, nanoparticles fraction, and fluid flow rate were examined, with slight performance improvements noted for lower PCM melting points and nanoparticles dispersion. Kuang et al. [10] conducted a comparative analysis to predict the performance of evacuated tube solar collectors using three different methods: Convolution Neural Network (CNN), Multiple Linear Regression (MLR), and Back Propagation (BP) neural networks. Their research revealed that the CNN model surpassed both MLR and BP neural network models in terms of prediction accuracy, exhibiting the lowest root mean squared error and the highest coefficient of determination.

On the above section various papers have been studied based on PCM application in solar collector. Therefore, it can be summarized from the aforementioned literature on that PCM plays very important role in solar collectors to enhance the performance of the solar collectors. Also, the solar collector performance can also be enhanced by utilizing the other HTFs.

Solar energy can be harnessed for cooking, although with the limitation that it primarily operates during daylight hours. To address this constraint, solar cookers can be outfitted with thermal storage units, enabling food preparation even in overcast conditions or during night-time. Over the years, a variety of solar cookware designs, including box cookers and parabolic dish cookers, have been employed to harness this sustainable energy source for cooking purposes [11]. In a review conducted by Lentswe et al. [12], they assessed parabolic solar cookers equipped with thermal energy storage systems. Their findings indicated that the majority of the research in this field has focused on using latent heat storage, rather than sensible heat storage, particularly for high-temperature cooking applications with box-type solar cookers. Kumaresan et al. [13] performed an experimental investigation to evaluate the performance of a solar parabolic trough collector (PTC) integrated with a thermal energy storage system and examined it over the course of a full sunny day. The key findings revealed that PTC efficiency is most favourable between 8:00 AM and 9:00 AM due to incident beam radiation and useful heat gain. The PTC achieves peak efficiency at noon, reaching an impressive 62.5%. To improve drying performance, Pandiaraj et al. [14] used a solar rack drier arrangement in an experiment. The system used a parabolic trough and a passive heating coil that was extended from a header of a water-in-glass evacuated tube to increase heat in the collector section. Utilizing the enhanced dryer, this product required 1.27 kWh/kg of specific energy to dry. Energy efficiency in the drying chamber ranged from 4% to 45%, with an average of 16% for capsicum frutescence.

In their theoretical study, Hebbar et al. [15] examined the functionality of an evacuated tube solar cooker. This solar cooker was unique in its utilization of palm oil as a heat transfer fluid and Magnesium nitrate hexa hydrate (Mg (NO3)26H2O) as a phase change material. The research findings demonstrated that the temperature of the palm oil within the system reaches its peak in the late afternoon and gradually decreases afterward. Palanikumar et al. [16] three Solar Box Cookers (SBCs) were developed: one with a PCM made from waste cooking oil and C4H4O3, another featuring a novel SBC with a nanocomposite PCM (NPCM), and a third without NPCM. The cooker with NPCM raised the internal temperature to 164.12°C and showed an 11%

thermal performance improvement over the others. Overall thermal performance ranged from 24.90% to 56.21%, and bar plate absorber temperatures reached 163.74°C, 147°C, and 113.34°C under 1,037 W/m2 of solar radiation. Coccia et al. [17] a portable solar box cooker with a concentration ratio of 4.08 was studied in conjunction with thermal energy storage (TES) system utilizing a PCM called erythritol. The TES setup consisted of a double-wall stainless steel container containing 2.5 kg of erythritol in its annular space. The findings indicated that the inclusion of the erythritol-based TES substantially prolonged the average cooling time for loads within the 125°C–100°C temperature range, demonstrating an impressive increase of approximately 351.16%.

In the study conducted by Vishwakarma and Sinha [18] they carried a thorough examination of box-type solar cookers paired with a heat storage unit, synthesizing insights from prior experimental and analytical research endeavors. In their study, it was evident that among the various materials utilized for insulation, air exhibited the lowest energy efficiency, whereas coconut coir emerged as the most effective and energy-efficient choice. Lecuona et al. [19] constructed a solar cooker by combining a TES unit with a conventional focusing parabolic dish. The thermal storage materials employed in this setup consisted of erythritol and technical-grade paraffin. This approach highlights the importance of both the design elements and the choice of thermal storage materials in the development of effective solar cookers. Dhiman and Sachdeva [20] invented an innovative indirect type solar cooking system for indoor cooking purposes. Throughout their investigation, the system effectively elevated the temperature of the heat transfer fluid to an impressive 175°C. Moreover, the proposed system exhibited an average thermal efficiency of 13.11% over the course of an entire day, highlighting its promising potential for sustainable and efficient cooking. Uniyal et al. [21] performed a 3D simulation for an evacuated tube solar collector with different phase change materials (lauric acid, paraffin wax, stearic acid). They assessed heat transfer and melting under varying solar conditions from 09:00 to 13:00. Lauric acid melted most (about 95%), stearic acid the least (57.4%), making lauric acid suitable for low solar areas. Sagade et al. [22] introduced a versatile solar concentrating cooker designed to fulfil both cooking and heating requirements. The research incorporates the Cooker Opto-Thermal Ratio (COR) as a thermal performance parameter and conducts an economic assessment through the levelized cost of cooking a meal. Notably, the system consistently maintains a COR value at approximately 0.0908, indicating its reliable and consistent performance. Furthermore, the efficiency of water heating is observed to vary with different flow rates, ranging from 0.57% to 0.81%.

The difference between the present study and the other study is that the present study has uses Acetanilide as PCM and SigmaTherm–K as HTF. Various studies performed on different HTFs such as Singh et al. [23] conducted a comprehensive investigation into the impact of using two HTF, namely water and engine oil, on the performance of a solar cooker integrated with an evacuated tube solar collector. Their research revealed significant differences in temperature outcomes. When 600 ml of water was employed as the working fluid, the highest HTF temperature inside the cooker reached 98.5°C. In contrast, when motor oil was used, this temperature increased to 105.5°C. These findings underscore the significant influence of the choice of HTF on the solar cooker's performance. Esen [24] conducted a detailed investigation into the performance of a solar cooker utilizing a refrigerant for heat transfer from the collector to the heat storage unit. In this study, a heat pipe was constructed, featuring three distinct refrigerants: R407c, R22, and R134a. The research aimed to understand the relationship between various factors, including the thermophysical characteristics of the refrigerant and meteorological conditions, and their impact on the cooking duration within a solar cooker. The study's findings underscored the intricate interplay between these factors in determining the efficiency of a solar cooker. Harikrishnan et al. [25] delved into the effectiveness of heat pipes employed in ETSCs, conducting comprehensive evaluations under varying conditions. To scrutinize the heat pipe's behavior, the experiments incorporated both evacuated tube collectors and parabolic collectors. One significant observation was that heat pipes with a 60° inclination within the evacuated tube collector outperformed those with a 35° inclination. Ultimately, the study's key finding emphasized the optimal fill ratio for heat pipes in this context. It was concluded that the most efficient heat pipes are those where the working fluid is filled to a volume equivalent to 25% of the evaporator volume. This outcome highlights the importance of meticulous fluid selection and appropriate fill ratios when aiming to maximize the performance of heat pipes within ETSCs.

In contrast to much of the existing literature, which commonly utilizes water as HTF due to its widespread availability, this study explores the potential of SigmaTherm–K as an alternative HTF. Additionally, the research employs Acetanilide as the PCM. The selection of PCM and HTF in many cases hinges on factors like heat capacity, cost, and availability. A distinctive aspect of this study lies in its introduction of SigmaTherm–K as an HTF, offering a comparison with the conventional choice of water. Moreover, the research underscores the importance of considering pipe insulation versus non-insulation in the context of this innovative approach. The objective of this study is to experimentally compare the thermal performance of a solar cooker based on ETSCs with various HTFs and with PCM. The research is conducted in the typical climate of Delhi, India.

EXPERIMENTAL SETUP

An ETSC with solar cooker setup is shown in the Figure 1. The cooker is connected to the ETSC with the pipeline.

The main objective of the present experiment to calculated the performance of the solar cooker with ETSC. The experiment's setup consists of the following components: a cooking unit, a heat pipe with HTF, an ETSC. Figure 2 represents structure and geometric properties of the evacuated tube. The dimension of the solar cooker has been taken as 200 mm diameter and 100 mm of height having silver as the cooker material. It is made up of an evacuated tube that has double glass walls that are concentric to each other. One end of the tube is closed, while the other end of the tube is open. The area in between the two concentric tubes is evacuated to produce a vacuum. This ensures that there will be no heat loss due to conduction or convection and that any solar rays that penetrate the evacuated tube and absorbed by the heat pipe that is located inside the evacuated tube. However, the photograph of the of the solar cooker with insulation can be seen in Figure 3. A heat pipe is a pipe used to transfer heat from a collector to a heat sink. The heat pipe is shown in Figure 4. It is constructed from a highly conductive material to ensure rapid heat transfer from one end to the other. A HTF is contained within the heat pipe and is responsible for transporting heat from the hot collector to the cold storage unit. High thermal conductivity and thermal diffusivity are required, along with low viscosity and corrosion resistance in an HTF.

SigmaTherm–K [26] is used as HTF to carry heat from the collector to the cooking unit. SigmaTherm–K is synthetic oil made from short length of a straight and saturated chain of Alkyl group. It has good properties of oxidation resistance, low carbon deposits, thermal stability, low rate of evaporation loss at low operating temperature and viscosity and cost effective. PCM serve as an energy backup source to SigmaTherm–K. The PCM materials make it possible to store excess thermal energy and utilize it at a later time if needed. Both sensible heat and the latent heat of fusion can be stored in this way. In this experiment, acetanilide serves as the PCM. Acetanilide is a colorless, odourless, solid chemical that resembles leaves or flakes and low cost. Formerly sold under the brand name Antifebrin, it is now more commonly known as its chemical name, acetanilide.

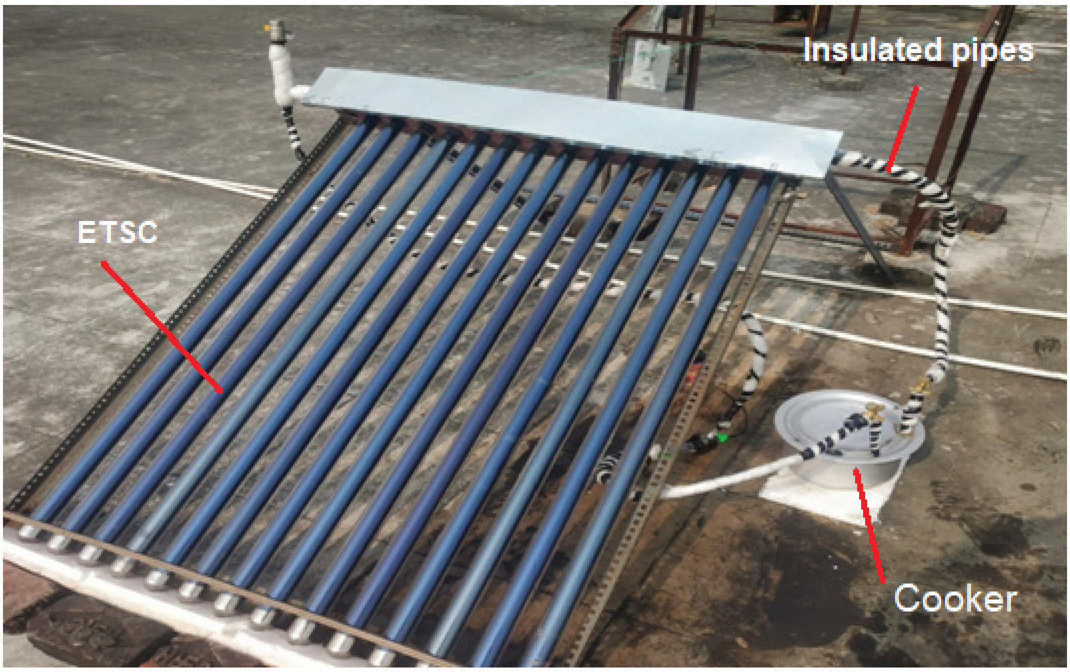

Figure 1. Evacuated tube solar cooker contains solar cooker without insulation.

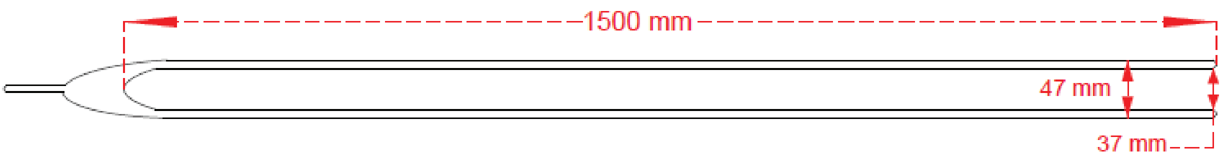

Figure 2. Schematic diagram of the side view of the evacuated tube.

Figure 3. Photograph of the solar cooker with insulation.

In the old school of organic chemistry labs, it was made by mixing acetic anhydride and aniline [27]. Solar cooker is constructed using two cooking utensils, copper pipe, PCM named acetanilide, a ball valve, and a pump. The diagram of the solar cooker is shown in Figure 5. The flowing of SigmaTherm-K and water can be seen in photograph of Figure 6 and Figure 7 respectively. Two cooking utensil is used to construct a solar cooker; the smaller utensil is placed inside the bigger utensil. The bigger utensil has a 25 cm diameter and14.5 cm depth whereas smaller utensil has an 18 cm diameter and 9 cm depth. The heat transfer coefficients and thermal conductivity were as 23 W/m^2°C and 120 W/m°C of the cooker unit. The space between the two utensils is filled with PCM named acetanilide and the amount of acetanilide is 3.5 kg. The melting point of the considered PCM is 114.3°C. Three-hole is drilled in the top holding of the utensil and from which two holes are used to pass a 3/8" copper pipe carrying heat transfer fluid SigmaTherm- K [28–31].

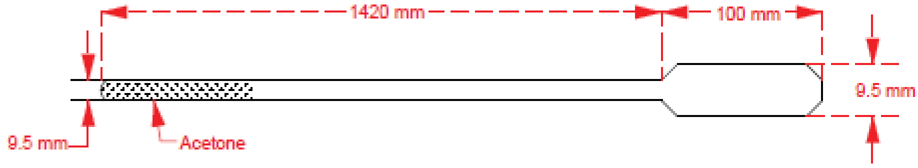

Figure 4. Schematic diagram of the heat pipe.

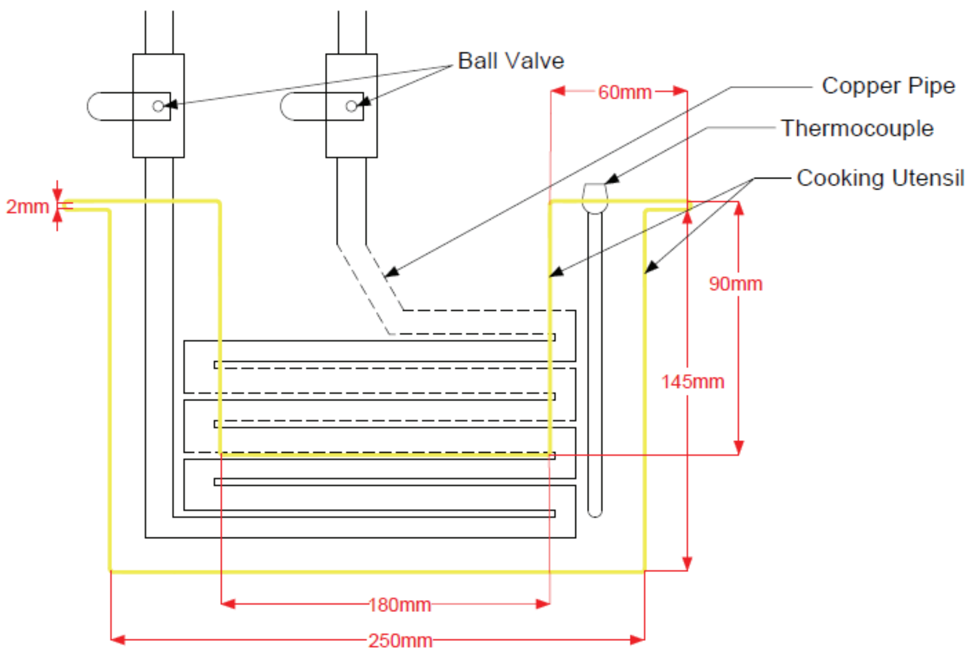

Figure 5. Schematic diagram of solar cooker.

Figure 6. Photograph of SigmaTherm–K as HTF.

Figure 7. Photograph showing water as HTF.

The following tools are used to measure the properties of the system. *Temperature sensor:* With an accuracy of +1°C, this sensor (model TPM-10) can be utilized for measuring temperatures between -50°C and 110°C. ApTechDeals Company is the manufacturer of this temperature sensor. *Whirling hygrometer:* This instrument is used to measure the temperatures of both wet and dry bulbs. Up to 20°F can be measured using it. An anemometer measures the wind's speed, which influences how hot or cold the ETSC is. The anemometer has a velocity range of 0–45 m/s and an operational temperature range of 10°C–50°C and humidity range of 40–85% relative humidity, respectively. The ambient and testing fluid temperatures were measured using two T-type thermocouples, and the remaining temperatures were determined using K-type thermocouples. Direct normal irradiance was measured using an Eppley NIP (Normal Incidence Pyrheliometer, +0.5% in the range 0-1400 W/m^2).

Analysis of Experimental Data

The amount of heat energy (Q_{in}) required to boil water in the cooker, considering the ambient temperature as 30°C is given by [15];

$$Q_{in} = m_w \times C_{p,w} \times \Delta T \tag{1}$$

Where, m_w and $C_{p,w}$ are the mass flow rate and specific heat of water respectively.

The amount of heat gained by the HTF is given by [15];

$$Q_{HTF} = m_{HTF} \times C_{p,HTF} \times \Delta T \tag{2}$$

Where, m_{HTF} and $C_{p,HTF}$ are the mass flow rate and specific heat of HTF respectively.

Energy stored by PCM is given by as [27];

$$Q_{PCM} = m_{PCM} \cdot [C_{PCM} \cdot (T_m - T_i) + L + C_{PCM} \cdot (T_{max} - T_m)] \tag{3}$$

Where, m_{PCM} and C_{PCM} are the mass flow rate and specific heat of PCM respectively.

It is assumed that the specific heat for the solid and liquid phases of PCM is the same.

RESULTS AND DISCUSSION

The main objectives of this experimental setup were to assess the thermal performance of solar cookers based on evacuated tube collectors employing different HTFs. The experiments were run in November 2022. The majority of the day's temperatures were between 18°C and 34°C. The solar collector was left exposed to the sun for eight hours every day, with readings taken every sixty minutes beginning at 8:00 am. All data has been taken 4-5 times to take accurate results.

On day one, the PCM is charged with water to act as the HTF, and both valves are left open while the cooker is left without insulation. On a solar cooker with an evacuated tube is put to the test without any insulation between it and the water being heated. The collector inlet temperature and outlet temperature were observed as 58.4°C and 67.7°C respectively, and the cooking utensil temperature was 60.8°C. During the day, the intensity peaked at 818 W/m^2 at 14:00 hr of the day and the ambient temperature range were 18.0°C to 23.1°C. Time increases the radiation intensity increased to it maximum value. Also, temperature of fluid increased due to high heat extraction. The variation

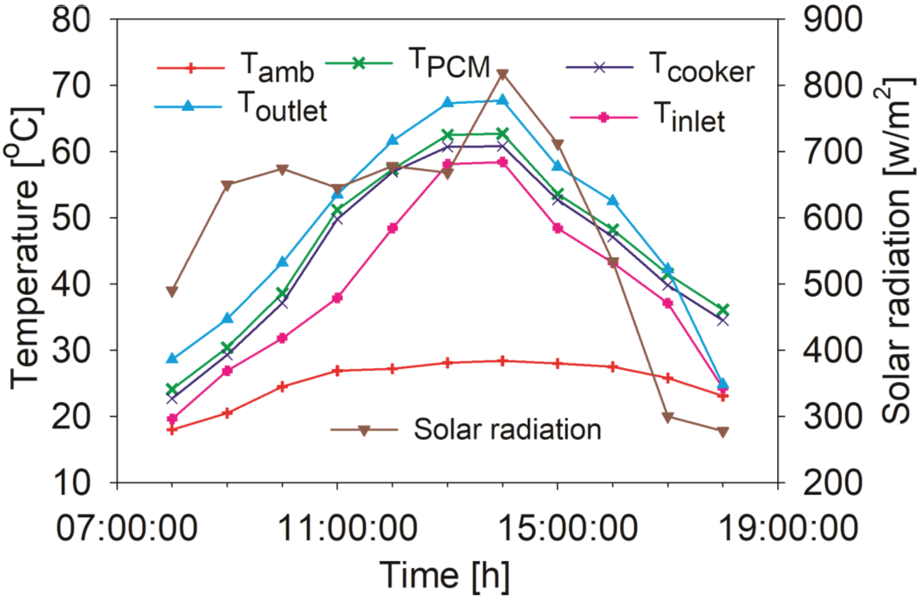

Figure 8. Variation of performance with time taking water as HTF without insulated cooker.

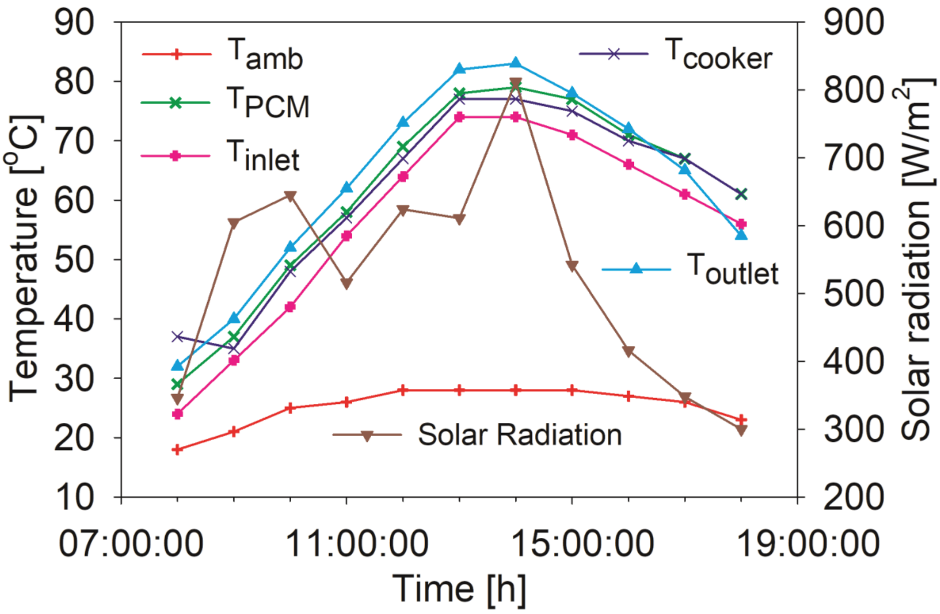

Figure 9. Variation of performance with time taking water as HTF with insulated cooker.

of the temperature of the different parts of experiment and solar irradiation are plotted in the Figure 8 with varying time conditions. Figure 8 can be considered as the reference case for the other conditions tested in this experiment.

On the second day, both valves are open during PCM charging with water as HTF, and the cooker is insulated. The experimental setup was tested with insulated cooker considering water as HTF this time also. In this result the maximum temperature of PCM was obtained 79.2°C at 14:00 hr, however the temperatures at the collector inlet, collector outlet, and cooking utensils were observed as 74.9°C, 83.5°C, and 77.5°C respectively at the same time. It can be observed from the Figure 9 the all temperature values increased and then decreased. As the time increased solar intensity increased which leads to high solar heat incidence. Consequently, temperature followed similar pattern to radiation. The ambient temperature ranged from 18.4 to 23.7°C, and the intensity peaked at a maximum of 812 W/m^2 during the day as seen in Figure 9. It can be seen comparison to the Figure 8 the maximum PCM temperature

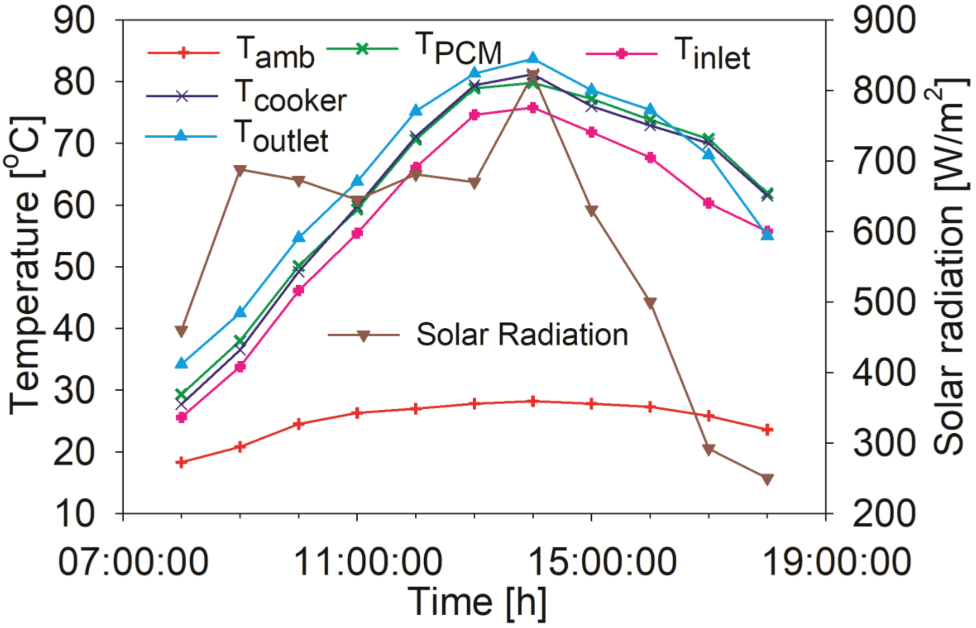

Figure 10. Variation of performance with time with insulated cooker with the cooking load.

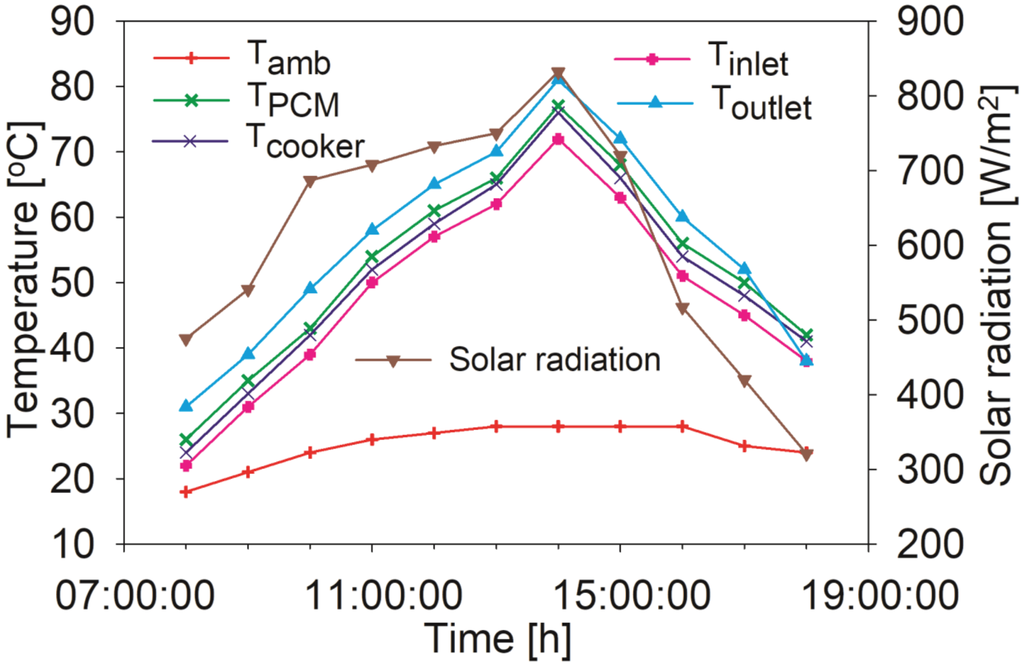

Figure 11. Variation of performance with time without insulated cooker with SigmaTherm–K.

was obtained more that of without insulation. Also, temperature at the collector inlet more than without insulated cooker due to heat is restricted to transfer and transferred to the PCM.

On day three, valves were opened however, the PCM is being charged with water to serve as the HTF, and cooker is insulated with the cooking load. In test the cooking load is taken in the solar cooker and performance were compared with the reference conditions as described in Figure 8. The results of an experiment using an evacuated tube solar insulated cooker and that was filled with 500 mm of water were plotted in Figure 10. The experiment was tested from 10:00 AM to 13:00 PM afternoon. The heat is transferred from the collector to the cooker using water as the HTF. The results are depicted in Figure 10, which reveals that the PCM reached its highest temperature of 79.8°C at 14:00 hr, while the temperatures at the collector inlet, collector outlet, and cooking utensils were, respectively, 75.8°C, 83.7°C, and 81.2°C. The temperature ranged from 18.3°C to 23.6°C, and the intensity peaked at a maximum of 823 W/m^{2}during the day. If compared it base case with Figure 8, this test type performed better than that of the reference conditions. In this case the 8.45% of the temperature of the PCM increased as compared to reference case.

On day four, the valves are left open and now SigmaTherm-K is added to the PCM as HTF, and the cooker is left without insulation. As seen in Figure 11, the efficiency of an evacuated tube solar cooker is evaluated by using SigmaTherm-K as a HTF between the collector and the without insulated cooker. In this setup maximum temperature of the PCM was reached to 77.4°C at 14:00 hr, while the temperatures of the collector inlet, collector outlet, and cooking utensils were obtained as 72.5°C, 81.7°C, and 76.8°C, respectively. Also, the maximum intensity during this day was 832 W/m^2, and the ambient temperature was varied from18.7°C and 24.1°C. In this test the temperature variation pattern is same as the previous one however values were higher than that previous due to it HTF combination gave highest heat absorbing capacity. Consequently, temperature increased. This variation can be seen in the Figure 11. Comparing the Figure 8 and the Figure 11, it can be seen that this setup performed better than the reference conditions. On the fifth day, both valves are open during PCM charging with SigmaTherm-K as the HTF, and the cooker is insulated. An evacuated tube solar cooker is being tested, which is insulated with glass wool insulation and uses SigmaTherm-K as HTF. During the time as depicted in Figure 12, the collector inlet, collector outlet, and cooking utensils all reached temperatures of 93.2°C, 99.6°C, and 95.4°C, respectively, while PCM reached its maximum temperature of 96.7°C. Here PCM reached to its highest temperature because the cooker is insulated and SigmaTherm-K was used simultaneously that have better heat absorbing capacity. Intensity peaked at 812 W/m^2 during the day, with ambient temperatures range from 18.2°C to 24°C. Comparing with the above cases this system gave the highest temperature of PCM and inlet to the ETSC system.

Day sixth: in this last day solar cooker performance was tested with insulated cooker with cooking load using the SigmaTherm-K as the HTF. As the cooking load solar cooker was filled with 500 ml of water from 11:00 hr to 13:00 hr and recorded results were plotted on the Figure 13. SigmaTherm-K is used to transfer heat from the collector to the cooker. As can be seen in the Figure 13 highest temperature of the was recorded as 97.5°C at 14:00 hr, and the temperatures at the collector inlet, collector outlet, and cooking utensils were recorded as 92.4°C, 99.4°C, and 96°C respectively at the same time. These temperatures were observed as the highest temperatures of the above test performed. This test gave highest performance of solar cooker due to the better heat transfer catachrestic of the selected HTF in this test. Maximum temperature of the selected points was observed at the 14:00 PM due to highest solar irradiance in India. During the day, the sun was the strongest at 839 W/m^2, and the temperature ranged from 18.5°C to 21.8°C. As the cooking load 500 ml of water is boiled, with specific heat 4.182 kJ/kg°C, its temperature raised from 20.1°C to

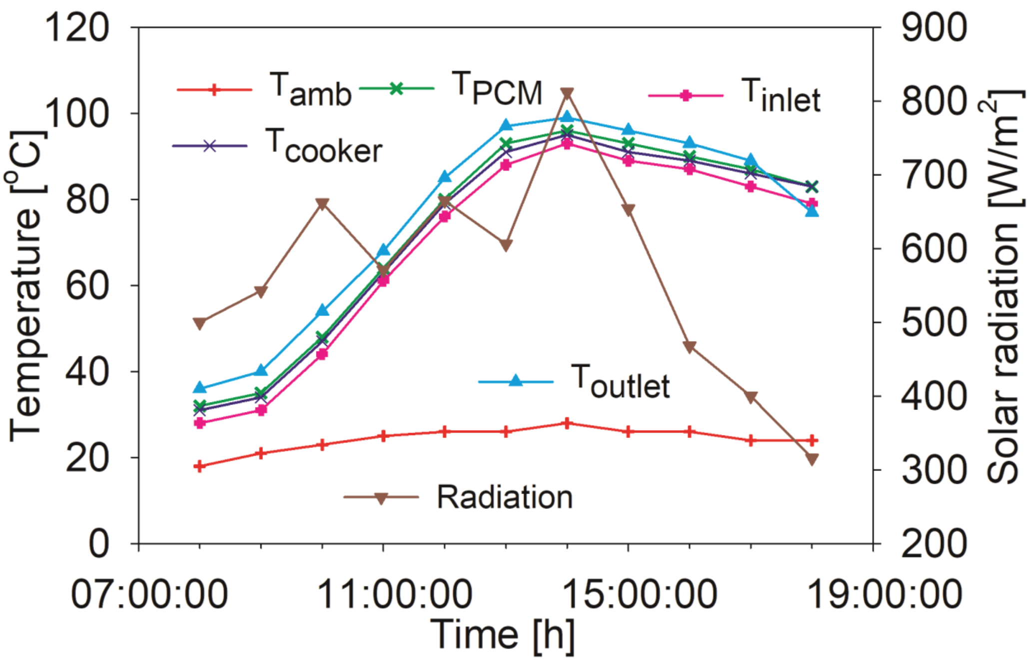

Figure 12. Variation of performance with time with the insulated cooker with SigmaTherm–K.

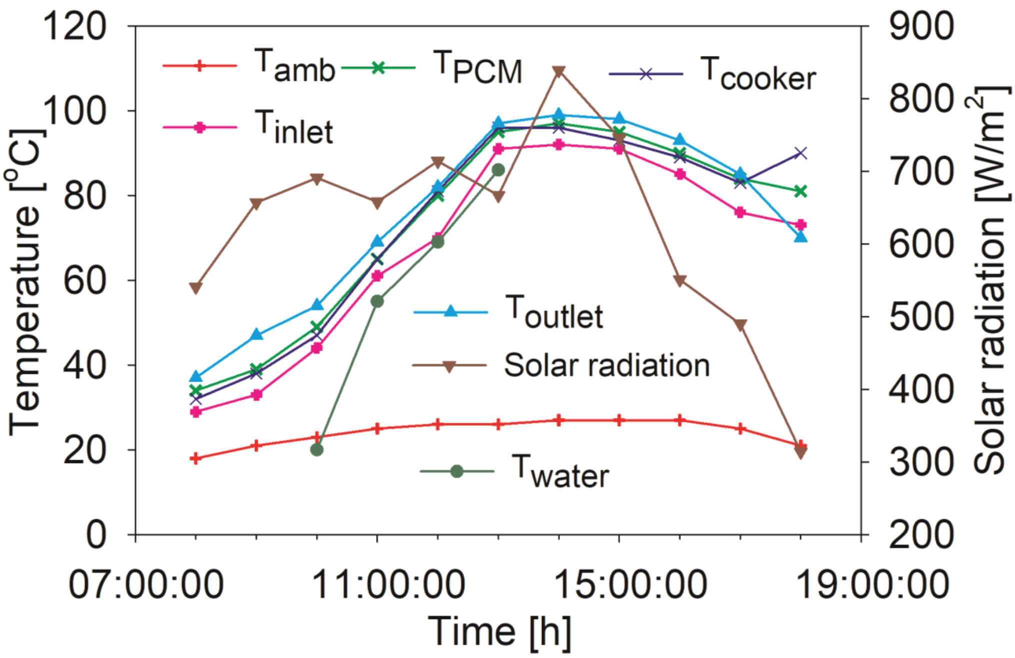

Figure 13. Variation of performance with time with insulated cooker containing SigmaTherm–K with the cooking load.

86.2°C. The practical application of the solar cooker is to cook the food in the areas where abundant sun light is available such as tropical countries.

CONCLUSION

The presented experimental setup demonstrates the following result:

- It was determined that heat stored by PCM using SigmaTherm–K as stored 29.11% more heat than that of water.
- The maximum temperature attained by PCM in insulated cooker is 16.5°C higher than that of without insulated cooker using water as the heat transfer fluid.
- The maximum temperature attained by PCM in the insulated cooker is 19.3°C higher than without insulated cooker using SigmaTherm–K as the heat transfer fluid.
- The temperature attained by water as cooking load increased from 22°C to 77°C and from 20.1°C to 86.2°C using water and SigmaTherm–K as a heat transfer fluid respectively.
- It was concluded that the using SigmaTherm–K with PCM solar cooker obtained the best performance among other testing conditions.
- The future research is to discuss the detailed exergy analysis of the present system.
- This research is beneficial to climate conditions and has the reasonable solar cooker efficiency with the selected HTF and efficiently utilized the solar energy.
- This research is the limited to the peak load conditions only i.e. at the peak solar radiation conditions.

NOMENCLATURE

Q_{PCM}	Heat stored by PCM (kJ)
m_{PCM}	Mass of PCM (Kg)
C	Specific heat (kJ/kg°C)
T	Temperature (°C)
T_m	Melting temperature of PCM (°C)
$T_{PCM, max}$	Max temperature attained by liquid PCM (°C)
T_i	Initial temperature of PCM (°C)
L	Latent heat of fusion (kJ/kg)
PCM	Phase change material
HTF	Heat transfer fluid
T_{amb}	Ambient temperature (°C)
ETSC	Evacuated tube solar collector

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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