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CONTEMPORARY ADVANCEMENT IN SOLAR ENERGY ENGINEERING

Cooking performance assessment of a phase change material integrated hot box cooker

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Abstract

Previous research on solar box cookers focusing on the bulk usage of energy storage materials is a costly technique for performance enhancement. Bulk energy storage materials take much time to charge and, thus, result in a low rate of cooking at the start. Therefore, a hot box solar cooker has been developed and experimentally studied for thermal performance enhancement in a hilly region of Uttarakhand, India. A bed of phase change material (paraffin wax) filled with small capsule-shaped containers was prepared (detachable) and placed over the cooking tray of the tested cooker. These containers were vertically positioned over the bed to enhance the heat transfer rate inside the cooker to attain a fast-cooking response. Notably, the combined effect of extended geometry with PCM is an excellent method to increase the efficiency of a solar cooker. As per the author's knowledge, likely techniques have not been studied for a box cooker to achieve a fast-cooking rate in any hilly region up to date. The results of cooking tests show that the cooking plate attained a maximum temperature of about 150 °C. It is because of the combined effect of extended fins (vertical capsules) and PCM filled inside them. The results of the experimental study show that the thermal efficiency of the cooker was found to be about 45.7%, the cooking power was calculated about 54.71 W, the heat transfer coefficient was estimated about 311 W/m^2 °C, and the overall heat loss coefficient was computed about 5.71 W/m^2 °C. This modified cooker costs about $48.19, and the payback period is about 03 years and 11 months. Cooking trials also showed that the present SBC could cook almost all the dishes commonly cooked in Uttarakhand.

Keywords Solar cooker · Paraffin wax · Thermal storage · Thermal performance

Introduction

Solar energy is a boon for everyone on the earth. It serves in different ways to fulfill the energy demands of people from different regions in a non-polluting manner. Solar energy technology is commonly used worldwide for heating, cooling, and power generation. Figure 1 shows the world's capacity for solar thermal and electrical power. Besides this, solar-rich countries use this free energy source to fulfill their heating and cooling demands through solar water heaters, solar cookers, solar air heaters, solar stills, solar dryers, solar ponds, PV panels, and solar thermal power plants.

Among the above applications, solar cookers are the only source to cook food and to reduce the biomass consumption generally used as a cooking fuel in remote locations or hilly areas (Weiss and Spork-Dur 2021). Through solar cookers, people from remote backgrounds or hilly regions can keep themselves healthy and save a lot of their time which is wasted on collecting biomass for cooking. It is the best application for sustainable development, which operates on clean energy technology. Continued research is going on solar cookers since the 1800s. Different researchers have made numerous efforts worldwide to optimize the design of solar cookers and for more efficient cooking performance under variable ambient conditions to achieve a fast-cooking rate (Saxena et al. 2011).

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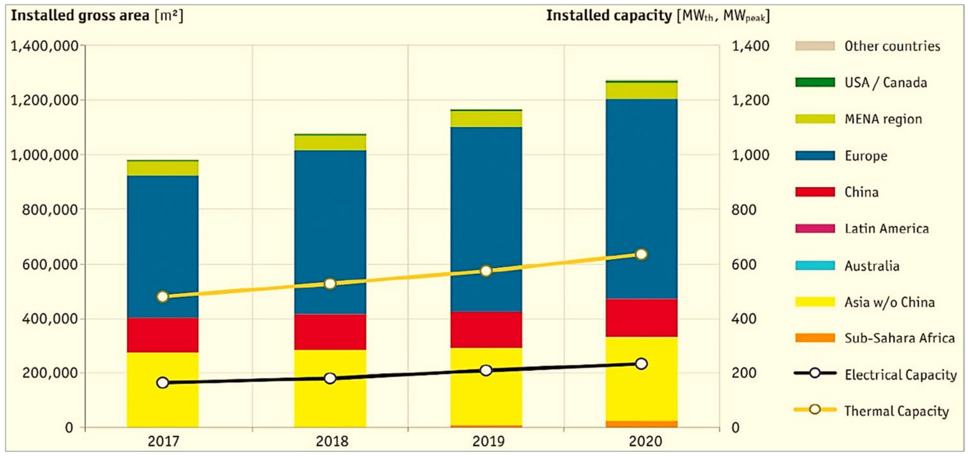

Fig. 1 World status of solar thermal and power generation capacity (Weiss and Spork-Dur 2021)

Literature review

This section focuses on the commonly used thermal heat storage (TES) materials that are used in solar thermal systems to enhance thermal efficiency and to maintain the thermal stability of the system after getting charged (through solar energy) to provide long-term heating and cooling effect. A literature review has been carried out for two major factors, i.e., the definition and classification of thermal heat storage and performance enhancement techniques for solar cookers.

Thermal heat storages

Storage of thermal energy (THS) is an effective technique for end-usage energy demand by energy redeployment. The energy available in heat/cold can be stored for a specific period and recovered from the same place for later usage. It is the standard concept of thermal energy storage, in which the "thermal" denotes either heat or cold (Dincer and Rosen 2011). This technique not only supports a thermal system for efficient operation but also extends the duration of operation due to energy storage. The classification of the THS has been given below, which is based on the state of matter and mode of heat storage in Figs. 2 and 3, respectively.

1. *Sensible heat storage (SHS)*. In sensible energy storage, energy is stored through a temperature change of the storage intermediate such as rocks, bricks, water, and sand. The volume of energy input (Q) to energy storage media from a sensible heat system is just proportionate to the temperature difference (Δt) of the storage's final and initial state, the mass of the TES material (m), and its heat capacity (C_p). There is no phase change

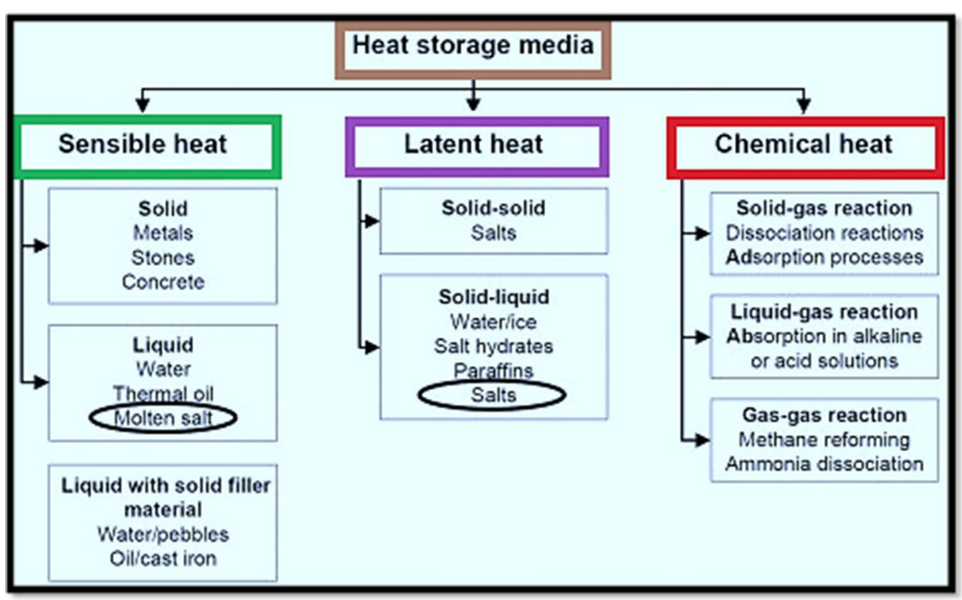

Fig. 2 Thermal heat storage based on state of matter (Weiss and Spork-Dur 2021)

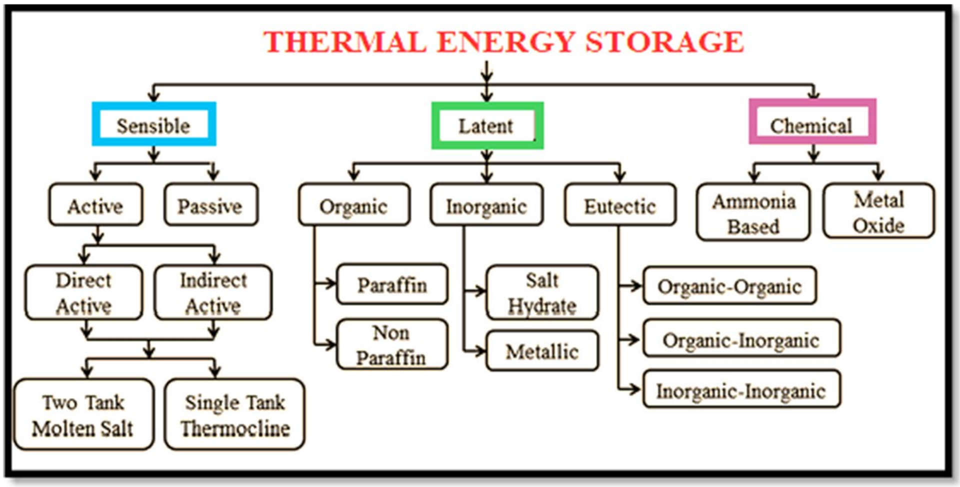

Fig. 3 Thermal heat storage based on mode of heat storage

occurred in sensible materials during the temperature variation during the heat storage process (Dincer and Rosen 2011; Alva et al. 2017). The amount of heat energy stored can be obtained as $Q = mC_p.\Delta t$.

2. *Latent heat storage (LHS)*. In latent energy storage, energy storage is stored through a phase change of the storage medium, and material is known as PCM. Heat transfer takes place if a matter changes its phase from one to another (which is known as the latent heat of the matter). This heat change is typically much higher than the sensible heat transformation for a specified media (i.e., related to its C_p). Like the SHS materials, the TES capacity (Q) of an LHS is equal to the sum of the latent heat enthalpy (H) at the temperature of phase change of the storage material $\{(C_p.\Delta t)_{\text{latent}}\}$ and the sensible heat existence over the temperature swipe $\{(C_p.\Delta t)_{\text{sensible}}\}$ of the TES process (Kalaiselvam and Parameshwaran 2014). This process can be expressed as $Q = m\left[(C_p.\Delta t)_{\text{sensible}} + H + (C_p.\Delta t)_{\text{latent}}\right]$.
3. *Thermo-chemical energy storage (TCES)*. In TCES, the chemical potential of a few matters is utilized on the base of storage and discharging heat energy with minute thermal losses. The revocable chemical interactions occur between the sensitive mechanism of TCES materials and the heat energy recovery in those materials (Bauer et al. 2013).

Apart from this, it is a fact that solar thermal systems require a large TES capacity to cover at least 1–2 days of heat demand. Such demand is usually fulfilled by SHS in large-size water tanks. However, an alternative is offered by LHS systems, where the heat is stored as latent heat in matters undergoing a phase transformation. The great advantage of LHS is its high heat storage capacity compared to SHS materials; therefore, in the present study, paraffin wax is considered for solar cooking operations.

Solar cookers with and without thermal heat storage

This section shows the potential of various techniques through which the overall performance enhancement of solar cookers is possible. Table 1 shows some good designs of box-type solar cookers around the globe with different techniques (such as fins over the solar collector or on the bottom side of vessels, usage of multiple reflectors, dual-energy input, and transparent insulation use) of thermal performance enhancement including the usage of TES materials.

Table 1 shows that there have been numerous developments made on solar cookers. Still, the contribution of the TES materials (especially PCMs) is highly remarkable in enhancing the overall performance of box cookers. Through a high storage capacity PCM incorporation, the possibility of evening cooking is also possible. But the designs developed for box cookers to date are not in complete favor of consumers. The operation, maintenance, and parts replacement are complex in the above designs. Apart from this, further modifications are not easily possible in such solar cookers, especially those that use PCM beneath the absorber tray. Replacement of the tested PCM after completing its life cycle is not easy. Also, these cookers cannot be further modified or used as conventional cookers (in case of slow cooking requirements) whenever required. Therefore, there is a need to develop a system that acts like a performance booster and can be attached or detached easily per the user's requirement. Thus, a bed of PCM-filled small containers has been developed (which can be easily attached or detached from the SBC), and RT64 has been considered the potential PCM to operate the solar cooker. The heat transfer was also improved by using a bed of small PCM-filled containers.

Table 1 Highlights of some recent studies on box cookers

Authors	Design	T_{plate}	Efficiency	Outcomes
(Saxena and Karakilcik 2017)	Double glazing box type solar cooker using low-cost TES material	137 °C	37.1%	The composition of the sand and carbon powder was found to be the best low-cost SHS material
(Guidara et al. 2017)	A simple designed SBC coupled with 4 mirror reflectors for additional irradiance level	133.6 °C	-	F_1 value improved from 0.7 to 0.14 while the T_{plate} improved from 81.3 to 133.6 °C
(Ghosh et al. 2017)	Special glazing glass which is doped with low antimony with indium oxide coating SBC	-	-	The overall cooking performance of a single-glazed SBC with low indium oxide coated was found more suitable
(Nayak et al. 2018)	Finned cooking pot type solar box cooker	-	72%	The rate of heat transfer from the collector plate to cooking pot was enhanced due to the incorporation of extended fins
(Reddy et al. 2017)	A simple deigned SBC was tested by using paraffin wax as LHS	120 °C	-	An SBC with PCM as a TES was found as a great alternative to traditional cooking systems. Thus, an SBC was designed according to the cooking needs of the small family, especially night cooking
(Saxena and Agarwal 2018)	A novel hybrid SBC was designed and fabricated with a trapezoidal air duct to operate the cooker on forced convection	143 °C	45.11%	Concluded that just by utilizing 210 W of energy, this cooker can cook food in any climatic conditions
(Zafar et al. 2018)	An SBC incorporated with some L-shaped fins over its absorber plate with one internal and two external reflectors was designed and tested	145.3 °C	-	About 30% increment in absorber plate temperature was found when using an L-shaped rather than a commonly used absorber plate
(Cuce 2018)	Cylindrical box designed solar cooker using Bayburt stone as a SHS material	124.57 °C	35.3%	Bayburt Stone is an efficient TES for a solar cooker to achieve efficient cooking under low ambient conditions
(Rai and Srivastava 2019)	Developed a solar cooker with aluminum pots using PCM	142 °C	-	PCM filled aluminum pots were found to be more suitable for day time cooking
(Maina et al. 2019a)	Solar cooker with double compartment using PCM	166.7 °C	92%	The double-compartment SBC was designed and fabricated with stearic acid as PCM. The cooker was found appropriate for low-temperature cooking
(Weldu et al. 2019)	SHBC with different configuration of reflector by using aluminum cooking	148.7 °C	37.24%	Cooker performance can be enhanced through a tracking type mirror booster by using optimal angle as well as using a cooking pot of *Al*
(Cuce et al. 2020)	Doubled-glazed solar cooker using low-cost booster reflector and TES materials	-	7.47%	To maintain the heat capacity of SBC overnight, the thermal resistance of body should be as high as possible, and glazing was observed to be an essential element for solar cookers
(Saxena et al. 2020)	A standard box cooker was experimentally studied with cylindrically shaped tubes of copper made and filled by a composite of graphene and paraffin wax	140 °C	53.81%	Large-capacity energy storage was applied to the cooker inside a copper tube which showed economical, efficient, and clean cooking
(Coccia et al. 2020)	Portable solar cooker using booster mirror of 8 reflective panel	189 °C	25%	It has been observed that the erythritol-based is a stable PCM and augmented the use of a portable SBC when the sun was absent or intermittently
(Anilkumar et al. 2020)	A solar box cooker was developed by using optimum composition of thermal storage materials	106 °C	16.1%	Indoor cooking was possible through the optimum mixture of PCM (with more than 100 °C of T_{plate}) or some affordable sensible heat materials
(Milikias et al. 2020)	Solar cooker using TES (Myristic acid)	155 °C	-	The upgraded solar cooker was 20% superior to a conventional SBC at the same point across the sun
(Palanikumar et al. 2021)	Novel SBC with nanocomposite PCM ($MgAl_2O_4/Ni/Fe_2O_3$)	163.74 °C	56.21%	The performance of SBC and NPCM was increased by about 11%

Table 1 (continued)

Authors	Design	T_{plate}	Efficiency	Outcomes
(Al-Nehari et al. 2021)	SBC was placed under tilt position with tracking mechanism	172.75 °C	-	Tiltable SBC was built to fulfill the cooking needs of a family of about 04–05 members in low environmental conditions. The present model was used to improve institutional designs and provide the necessary details before starting operations
(Rinawa et al. 2021)	PCM enabled SBC with additional reflector	162.1 °C	-	Cooking could be done at any time of the day using a specially designed and customized PCM cook
(Vengadesan and Senthil 2021)	Finned cooking vessel SBC	138 °C	56.03%	The high contact between the water and the wings leads to enhanced heat transfer and better cooking performance of the tested SBC
(Kumar et al. 2022)	SBC using PCM in capsule shaped	167 °C	52.10%	The key objective of the present work was to investigate an improved designed SBC for the people of the Uttarakhand region. Cooking trials proved the feasibility of a fair adoption of this design

Overall, a box cooker has been designed in the present research work to achieve the following objectives,

1. An SBC that has improved cooking efficiency compared with a conventional SBC
2. An SBC that can cook a variety of edibles in reduced time compared with a conventional box-type cooker
3. An SBC that can cook almost edibles without damaging its nutrients, taste, and color
4. An SBC that can further be modified easily (without any change in its standard design)
5. A cost-effective SBC that is easy to adopt for any household, mainly for Indian families.

Upcoming sections focus on achieving the above targets in a simple and informative way.

Materials and methodology

In the present work, a simple conventional design solar hot box cooker (SHBC) was fabricated with locally available materials by considering the standards developed by Mullick et al. (1987), especially for box-type solar cookers. About the specification of the tested SHBC then, it has an aperture area of about 36 cm^2. Double glazing (sheet of transparent glass) of the approximate area of about 50 × 48 cm^2 was used to trap the solar radiant energy through the dark interior of SHBC. The distance was about 15 cm from the aluminum made blackened cooking plate to the lower glazing sheet. A mirror reflector (51 × 53 cm^2) was used for additional thermal gain, which fixed on the lid of the SBC. The specific area of the SBC was about 66 cm^2, while the height of the cooker was about 20 cm. Glass wool was used as an insulation material to prevent thermal losses. The cooker's cooking capacity was about 03–04 kg for different cooking stuff inside the 04 identical cooking vessels (01 L capacity), made of *Al* and coated dull black.

The main modification to the tested SHBC was encapsulated phase change material (PCM). A bed of PCM-encapsulated small-size copper-made capsules was developed to modify the cooker. All 140 small capsules were placed vertically on a thin blackened sheet (thickness = 0.5 mm) of *Al* and fixed with the help of metallic adhesive (thermal conductive glue). This bed was also coated dull black and simply placed over the cooking tray of the SHBC, as shown in Fig. 4.

About the PCM, then, a commercial-grade paraffin wax RT64 has been considered due to its superior thermo-physical properties. It has a T_{melt} of about 64 °C, a thermal storage capacity of about 251 kJ/kg, C_p of about 2.1 kJ/kg.K, a thermal conductivity of about 0.2 W/m.K, and a density range from solid to liquid of about 0.88 kg/L (20 °C) to

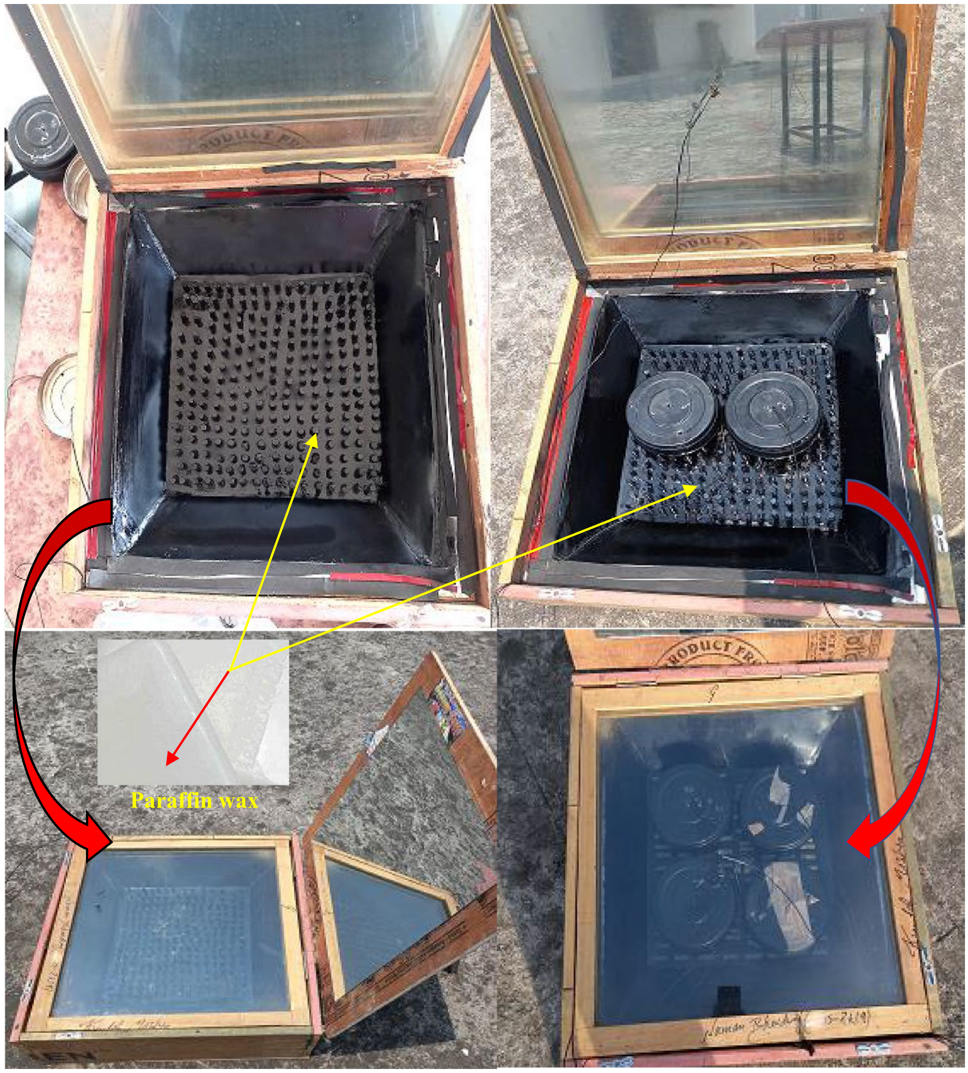

Fig. 4 Experimental setup of the present design of box cooker

0.78 kg/L (88 °C). This PCM was filled approximately 92% in the small capsules due to thermal expansion. A total of about 1.5 kg PCM was used. Noticeably, the specific size of the tested container was about 9.6 mm × 30 mm. The cost of the tested PCM is about $10.2, and the modified SBC costs approximately $48.19 (including PCM).

The modified SHBC was tested for its cooking performance in Dehradun city of the Uttarakhand state of India. The cooking trials were carried out on on-load and no-load conditions. The results are compared to the other existing models to determine the cost-effectiveness, cooking power, and mainly for the thermal efficiency. Following are the essential performance parameters to assess the thermal response of improved SHBC.

The first (F_1) and the second figure of merit (F_2) have been calculated by the given standard equations developed by (Mullick et al. 1987) as

$$F_1 = \frac{\eta_o}{U_L} = \frac{(T_p - T_{\text{amb}})}{I_{\text{in}}} \quad (1)$$

$$F_2 = F'\eta_o \cdot C_R = \frac{F_1(M_w C_{P-w})}{A_{\text{sbc}}.t} \text{In} \frac{\left[1 - \frac{1}{F_1}\left(\frac{T_{w1}-T_{\text{amb}}}{I}\right)\right]}{\left[1 - \frac{1}{F_1}\left(\frac{T_{w2}-T_{\text{amb}}}{I}\right)\right]} \quad (2)$$

It is notable that Mullick et al. (1987) established the F_1 for a no-load condition and F_2 for an on-load condition for solar cookers. They recommended the values of these figures to be in the range of 0.12 to 0.16 and 0.4 to 0.6, respectively.

The heat transfer coefficient (h) from the cooking plate of SHBC has been estimated by using the following equation (Hall et al. 1978):

$$h = \frac{Q_U}{A_{\text{sbc}}\left(T_p - T_f\right)} = \frac{\tau.I_{\text{avg}}.A_{\text{sbc}}}{A_{\text{sbc}}\left(T_p - T_f\right)} \quad (3)$$

Table 2 Measuring instruments used for experiments

Instruments	Parameters	Range	Accuracy	Resolution
Solarimeter	Insolation level	0 to 1200 W/m^2	± 1.8 W/m^2	2 W/m^2
Thermocouple sensor	Temperature variations	− 20 to 240 °C	± 1.5 °C	0.1 °C
Anemometer	Wind speed	0 to 25 m/s	± 2.1%	0.1 m/s
Weigh balance	Mass of the substance	0 to 8 kg	± 0.001 kg	± 0.001 kg

The coefficient of overall heat loss (U_{L}) has been estimated by summing the bottom and top loss coefficient (Mullick et al. 1997) as

$$U_L = \left[\frac{2.8}{\frac{1}{\varepsilon_P}\left(\frac{1}{N_c^{0.025}+\varepsilon_c} - 1\right)} + 0.825\left(x_m\right)^{0.21} + aV_{\mathrm{win}}^b - 0.5\left(N_C^{0.95} - 1\right) \right] \left(T_{\mathrm{pm}} - T_{\mathrm{amb}}\right)^{0.2} + \frac{k_i}{t_i} \tag{4}$$

where "a" and "b" are constant.

The cooking power of SHBC has been estimated through the standard relation between mass, specific heat, and the temperature of cooking stuff (Funk and Larson 1998) as

$$P_{\mathrm{sbc}} = m.c_p \frac{\left(T_{wf} - T_{iw}\right)}{600} \tag{5}$$

The thermal efficiency (η_{therm}) of the tested SHBC is estimated by considering the following equation (Hall et al. 1978):

$$\eta_{\mathrm{th}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}} = \frac{m.c_{p-w}.\Delta T}{t.I_{\mathrm{avg}}(A_{\mathrm{sbc}} + A_{\mathrm{cap}})} \tag{6}$$

where A_{cap} is about 5 cm.

Uncertainty analysis

It is essential to analyze the errors from the obtained outcomes of an experimental study. Notably, error and uncertainty occur naturally due to instrument selection, its condition, calibration, testing conditions, physical observations, and measurement of readings. Table 2 shows the instruments used in the present research work for taking readings of cooking trials, along with their accuracy and resolution.

The possible uncertainty in required thermal performance parameters due to instrumentation error has been estimated through a well-known method followed by Negi and Purohit (2005) and with the help of the following equations.

First figure of merit (F_1):

$$W_{F_1} = F_1 \left\{ \left(\frac{W_{T_p}}{T_p - T_{\mathrm{amb}}}\right)^2 + \left(\frac{-W_{T_{\mathrm{amb}}}}{T_p - T_{\mathrm{amb}}}\right)^2 + \left(\frac{-W_{(I)}}{I}\right)^2 \right\}^{0.5} \tag{7}$$

Second figure of merit (F_2):

$$W_{F_2} = F_2 \left\{ \begin{array}{l} \left(\frac{\partial F_2}{\partial m_w}\frac{W_{M_w}}{F_2}\right)^2 + \left(\frac{\partial F_2}{\partial C_w}\frac{W_{C_w}}{F_2}\right)^2 + \left(\frac{\partial F_2}{\partial F_1}\frac{W_{F_1}}{F_2}\right)^2 \\ \left(\frac{\partial F_2}{\partial t}\frac{W_t}{F_2}\right)^2 + \left(\frac{\partial F_2}{\partial A_{\mathrm{sbc}}}\frac{W_{A_{\mathrm{sbc}}}}{F_2}\right)^2 + \left(\frac{\partial F_2}{\partial T_{w_1}}\frac{W_{T_{w1}}}{F_2}\right)^2 \\ \left(\frac{\partial F_2}{\partial T_{w_2}}\frac{W_{T_{w2}}}{F_2}\right)^2 + \left(\frac{\partial F_2}{\partial \bar{I}}\frac{W_{\bar{I}}}{F_2}\right)^2 + \left(\frac{\partial F_2}{\partial \bar{T}_{\mathrm{amb}}}\frac{W_{\bar{T}_{\mathrm{amb}}}}{F_2}\right)^2 \end{array} \right\}^{0.5} \tag{8}$$

Thermal efficiency (η_{therm}):

$$W_{\eta_{\mathrm{th}}} = \eta_{\mathrm{th}} \left\{ \begin{array}{l} \left(\frac{W_{M_w}}{M_w}\right)^2 + \left(\frac{W_{T_{w2}}}{T_{w2}-T_{w1}}\right)^2 + \left(\frac{-W_{T_i}}{T_{w2}-T_{w1}}\right)^2 \\ +\left(\frac{-W_I}{I}\right)^2 + \left(\frac{-W_{A_{\mathrm{sbc}}}}{A_{\mathrm{sbc}}}\right)^2 + \left(\frac{-W_t}{t}\right)^2 \end{array} \right\}^{0.5} \tag{9}$$

Cooking power (P_{sbc}):

$$W_{P_{\mathrm{sbc}}} = P_{\mathrm{sbc}} \left\{ \left(\frac{W_{M_w}}{M_w}\right)^2 + \left(\frac{W_{T_{w2}}}{T_{w2} - T_{w1}}\right)^2 + \left(\frac{-W_{T_1}}{T_{w2} - T_{w1}}\right)^2 \right\}^{0.5} \tag{10}$$

Heat transfer coefficient (h):

$$W_h = h \left\{ \begin{array}{l} \left(\frac{W_{T_p}}{T_p-T_{\mathrm{amb}}}\right)^2 + \left(\frac{W_{T_{w2}}}{T_{w2}-T_{w1}}\right)^2 + \left(\frac{-W_{A_{\mathrm{sbc}}}}{A_{\mathrm{sbc}}}\right)^2 \\ +\left(\frac{-W_I}{I}\right)^2 + \left(\frac{-W_{A_{\mathrm{sbc}}}}{A_{\mathrm{sbc}}}\right)^2 + \left(\frac{-W_t}{t}\right)^2 \end{array} \right\}^{0.5} \tag{11}$$

Table 3 shows the instruments used for measuring the variations in temperature of various elements of the cooking system, including ambient, insolation, wind speed, and the mass of the cooking substance.

Uncertainty analysis of all the required performance parameters is carried out with the help of reference Negi and Purohit (2005). Table 3 shows the estimated uncertainties for different performance parameters such as F_1 has an uncertainty of about ± 2.27%, F_2 has an uncertainty of about ± 4.61%, η_{therm} has an uncertainty of

Table 3 The uncertainties of required performance parameters

Parameters	Uncertainty (%)
F_1	±2.27
F_2	±4.61
η_{therm}	±2.48
P_{sbc}	±2.41
h	±3.38

about ± 2.48%, P_{sbc} has an uncertainty of about ± 2.41%, and h has an uncertainty of about ± 3.38%. Figure 5 shows the error bar of the necessary TPPs. The significance of errors found within the permissible limit is because of calibrated instruments and correct measurements. The estimated uncertainty values in the required thermal performance parameters lie in an acceptable range and are on par with previous literature (Saxena et al. 2020; Cuce and Cuce 2013).

Regarding the calibration of the instruments, all the instruments are periodically (annually) calibrated through their manufacturer, i.e., Japsin industrial instrumentation, New Delhi. Notably, there is a Solar Radiation Resource Assessment (SRRA) station in Dehradun (installed at UPES, Dehradun). The authors have also measured the values of solar radiation, wind velocity, and ambient temperature from there (during the cooking trials), which were found close to the present experimental readings.

Results and discussion

In the present experimental study, efforts have been made to develop a low-cost and more efficient hot box cooker. A PCM encapsulation technique has been applied impressively to improve its cooking performance. The tested PCM was filled inside about 140 small capsules of aluminum. These capsules were vertically positioned on a flat plate to prepare a bed of the PCM capsules (Fig. 6), which acted like extended fins over the flat plate surface (cooking plate). This bed was placed inside the cooker to attain a high convective heat transfer rate inside the modified SHBC. Notably, a fast-cooking rate is observed through the applied technique for cooking the different edibles through the present design. This design is economical and easy to adopt for the people of remote areas and deep hilly regions.

Experiments were conducted on-load (stagnation heating test) and no-load (sensible heat test) conditions to assess the all-important thermal performance parameters for rating the cooking performance of the present SBC. Cooking trials were conducted in the summer season under the climatic conditions of Dehradun city, India, noticeable that the experiments were carried out on consecutive days in April 2022.

Stagnation heating test

In this test, experiments were conducted on no-load conditions, which means there was no cooking stuff inside the modified SBC. The sky was clear, and the day was sunny for cooking trials on 11.05.2022. The cooker was installed on the ground at 10:00 h to achieve the quasi-steady state condition. Around 10:20 h, the readings were taken at an interval of each 20 min during the one-h of standard stagnation heating test. At 10:20 h, the T_{amb} was observed at about 33.2 °C while the level of solar radiation was noticed to be about 600 W/m^2. At this time, the value of T_p was observed about 61 °C. Due to the encapsulated PCM inside the SBC, the T_p was found to be increased with

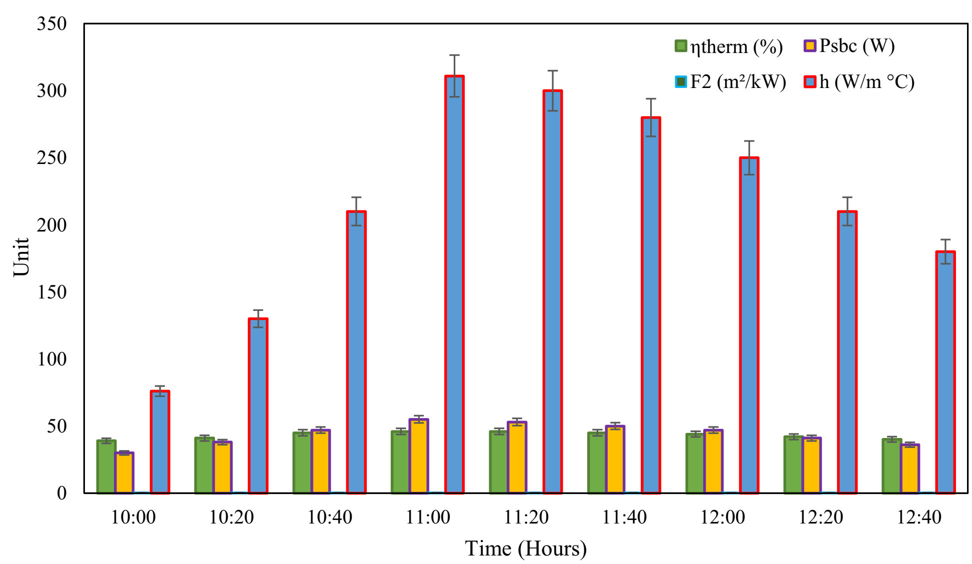

Fig. 5 Error analysis of the necessary performance parameters of the present box cooker

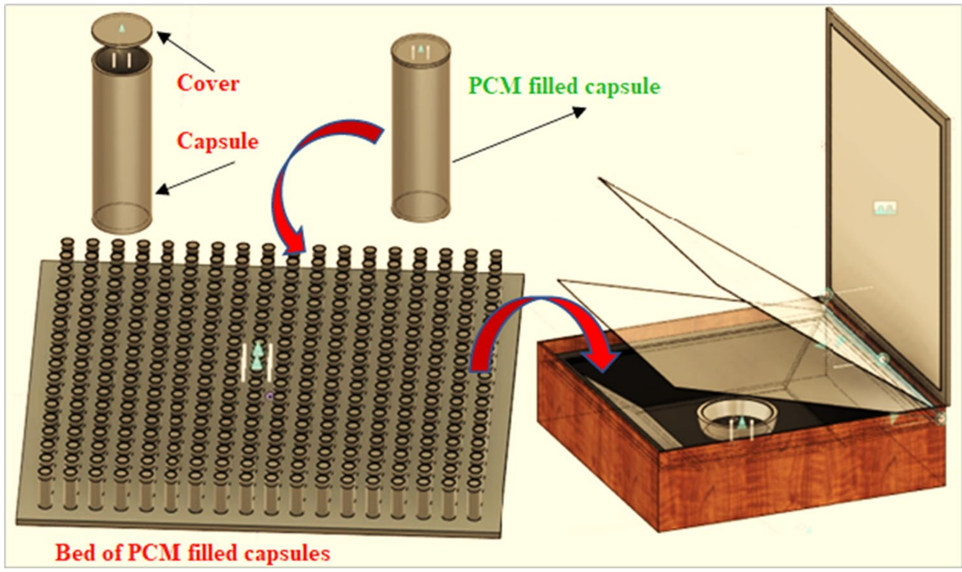

Fig. 6 Different elements of the modified SHBC

improved ambient conditions. Wind velocity (W_v) was observed at about 1.2 m/s over the horizontal surface near the experimental set-up. The peak value of the plate temperature was noticed at about 146.1 °C (T_{amb} = 37.2 °C) throughout the day while about 132.3 °C (T_{amb} = 35.1 °C) during the standard hour testing (recommended by BIS). The first figure of merit (F_1) was computed for a range from 0.12 to 0.15, which satisfied the standard. Figure 7 shows the thermal response of tested SHBC under stagnation testing.

Sensible heating test

In this test, experiments were conducted on on-load conditions. About 1 kg of water was taken as a cooking substance and filled for an equal amount in the two same-designed cooking vessels inside the tested cooker. The sky was clear, and the day was observed well for cooking trials on 12.05.2022. The cooker was installed on the ground at 10:00 h to maintain a steady state condition. Around 10:20 h, the readings started to be noted with an interval of each 20 min during the 1 h of the standard sensible heating test. Figure 7 shows that at 10:20 h, the T_{amb} was observed about 33.8 °C while the level of solar radiation was noticed at about 605 W/m^2. At this time, the value of T_p was about 67.7 °C, and the T_{wat} was observed to be 51.1 °C. Due to the encapsulated PCM inside the SBC, the T_p was noticed to be improved with improved climatic conditions, which resulted in increased water temperature. Wind velocity (W_v) was observed to be 1.4 m/s over the horizontal surface (over the experimental set-up). The peak value of the plate and water temperature were noticed at about 150.2 °C and

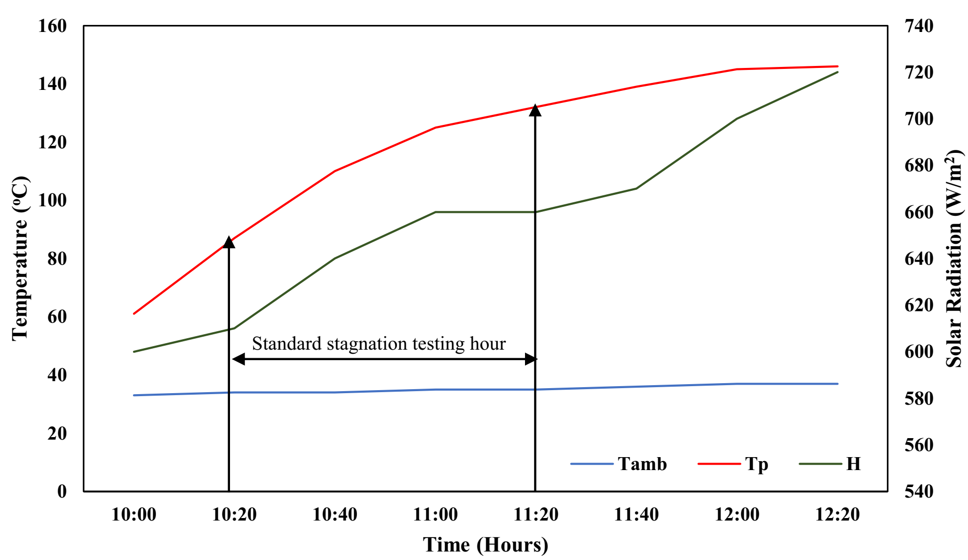

Fig. 7 Temperature curves of modified SHBC during the stagnation testing

97.7 °C (T_{amb} = 37.3 °C), respectively. Afterward, during the standard hour testing, these values were observed at about 138.1 °C and 96.88 °C (T_{amb} = 35.8 °C). The F_2 was computed for a range from 0.25 to 0.34.

Other required thermal performance parameters were obtained using Eqs. (1) to (6). The thermal efficiency (η_{therm}) of modified tested SHBC was found to be a maximum of about 45.7% with an average value of 42.1%, cooking power (P_{sbc}) was estimated at about 54.71 W, the value of HTC (h) between the solar absorber (tray), and the cooking vessel was assessed maximum for a range of about 76.01 to 311 W/m °C, and the value of U_{loss} was estimated maximum about 5.71 W/m °C. Figure 8 shows the thermal response of tested SBC under the sensible heating test. Notably, the modified cooker took about 105 min to attain the maximum value of the cooking plate and water during the experiments. The time taken "t" can be further reduced by improved ambient conditions during the long sunshine hours, especially in the summer. It has been observed that the T_{amb} and solar radiation significantly affect the thermal performance of the tested cooker. The T_p of the modified cooker is noted to increase and decrease significantly with a rise and fall in ambient conditions. However, the wind velocity (1.2 m/s) had a marginal effect on the cooking process, as described by Kumar (2004).

The results of the experimental study show that the PCM encapsulation supports the modified SBC to improve its cooking performance. This PCM encapsulation was done by filling the paraffin wax into a small size cylindrical-shaped capsule. With the help of 140 capsules, a bed of PCM-infused capsules was prepared to be placed inside the cooker. These vertically positioned capsules acted like an extended fin over a flat surface, as shown in Fig. 7, and likely geometries over a flat plate enhanced the convective and conductive heat transfer (Das 2011). In other research works, it has been experimentally studied that cylindrical shape fins are easy to design and more appropriate for obtaining a high heat transfer rate (Das 2014) compared with other designs of extended fins (Ranjan et al. 2021). Basically, the fins are the extended surfaces of conductive materials applied to an element to enhance the heat transfer rate to the environment due to increased convection. The amount of RCC of a body determines the approximate volume of the heat it transfers. The higher the temperature gradient between the element and surroundings, the higher the convection HTC. Notably, a large surface area of the element improves the heat transfer. Therefore, adding a fin to a component or system expands the surface area, and it is a cost-effective solution for thermal systems to enhance heat transfer (Nellis and Klein 2009). Figure 9 shows the different fins geometries for thermal systems.

If one can talk about using fins inside the SBC, then these fins enhanced convective heat transfer exclusive in SBC due to the large surface contact area. The hot circulated air inside the cooker supports the incident solar radiant energy. Therefore, cooking time is reduced through the enhanced radiative and convective heat transfer by achieving the boiling temperature in a short span of time.

Apart from this, macro encapsulation of PCM is the best methodology to enhance the thermal performance of solar thermal applications. Therefore, such a technique was applied to a simple design cooker for performance enhancement. RT64HC (Rubitherm 2020) was considered a potential PCM for encapsulation in a small cylindrical capsule due to its large volume capacity among the various extended geometries, as shown in Fig. 6. This encapsulation provides thermal stability to the SBC during interruptions in ambient conditions. The excellent thermo-physical properties of the tested PCM store the solar radiant heat during the solar hours and release the stored at a slow rate to the environment making evening cooking possible through the solar cooker.

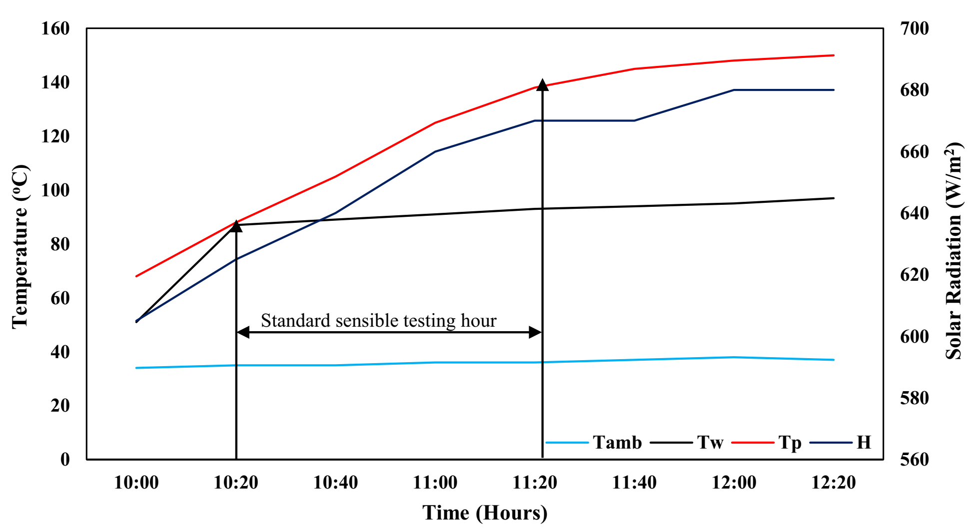

Fig. 8 Temperature curves of modified SHBC during the sensible heat testing

Fig. 9 Different types fins commonly used in thermal systems (Nellis and Klein 2009)

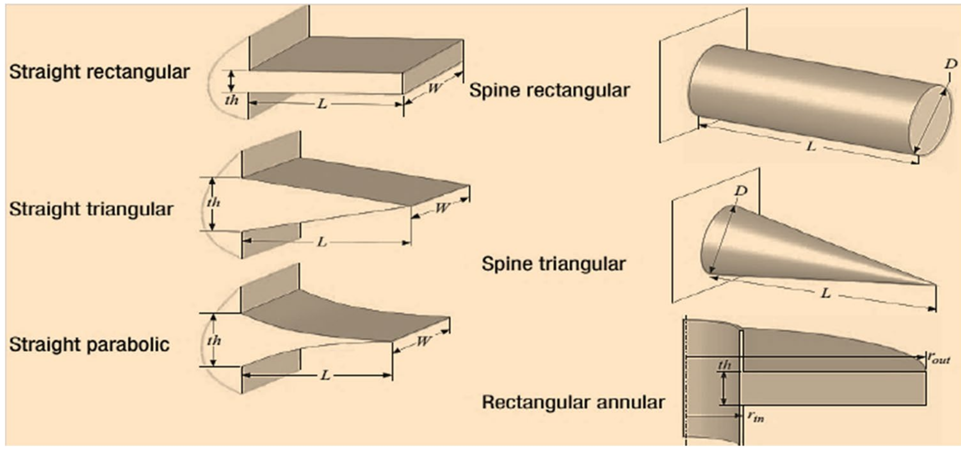

Table 4 Post experiments cooking results of the modified cooker

Cooked dishes	Mass	T_{amb}	Time taken (min)
Rice	0.80 kg	37.10 °C	76
Pulse (Hari moong)	0.75 kg	36.85 °C	72
Thin potato slices	0.60 kg	37.50 °C	61
Eggs	08 pieces	37.81 °C	85

Other available works also show that a large quantity of PCM takes much time to charge it completely (Saxena et al. 2020); therefore, a late response occurs in the heating or cooking process. Consequently, to overcome this problem, small-volume capsules has been considered in the present work for PCM encapsulation. Through this, the tested PCM has been charged faster that resulted in fast-rate cooking. The results of this study have been found useful, especially for enhancing the performance of solar thermal systems because of the collective effect of extended geometry and the tested PCM. The heat transfer rate inside the cooker was relatively better than an orthodox box cooker with improved thermal stability. Thus, the results were better, and a fast-cooking rate was observed during the cooking and post-cooking trials.

The newly developed cooker is also tested to cook different edibles after conducting standard cooking trials to obtain the required TPPs. In these cooking trials, commonly cooked dishes by the people of Uttarakhand were cooked on additional days after experimental cooking trials. Table 4 shows the cooking results of some other dishes that offer a fair possibility of adopting the tested cooker.

The current design of the modified cooker is also practically useful. One can easily use it as a conventional cooker whenever required. Besides this, this cooker can be further modified accordingly by simply detaching the PCM bed. This model also has the flexibility to perform around the year. A simple electrical coil of about 40 W can raise the PCM bed temperature to 125 °C; thus, cooking is possible in any climate at any geographical location. People can cook food by using the present cooker in a hybrid mode instead of using a microwave oven of 1 kW. Through this, a lot of electrical energy can be saved.

Comparative study

The present design of the cooker is quite economical and efficient for cooking food under low environmental conditions. All the cooking stuff available in local or nearby regions of Uttarakhand can cook inside the modified cooker under low or high ambient conditions. Apart from this, people from the hilly areas waste their time to collect biobased fuels, especially wood pellets and making dung cakes. Noticeably, the combustion of these low conversion efficiency fuels releases a bundle of pollutants that are too harmful to the consumer or nearby people. This cooker is feasible to reduce carbon emissions throughout the year with its potential use. Table 5 shows a comparative study of the current experimental study with some other cookers.

From Table 5, it can be seen that there are a lot of modifications made to the solar cooker in which very few cookers are considerable practically for solar cooking. Other solar cookers are complicated in design and occupy a large space, increasing the cost of cooking. Maintenance of complex designs is also too expensive. The cookers that function on PCM (in bulk) are not entirely safe from leakage problems, and a large volume of PCM increases the cost of the cooking system (too) and reduces the reliability. Thus, it is essential to estimate the optimum volume of the tested PCMs to be used in different solar energy applications.

The effect of a high heat storage material can also be noticed in other applications, such as solar stills (Dincer and Rosen 2011), photovoltaic systems (Wen et al. 2023), and solar air heating systems (Verma and Das 2022). All these

Table 5 Different designs of solar cookers and their results

Reference	Research work	Results
Saxena et al. (2011)	A novel cooking pot was designed to increase the cooking capacity of a standard SBC. The cooking vessels had lugs in the curvature form at the bottom side, which enhanced the convective HTC and decreased the cooking timings by about 30 min	The cooking time was reduced by about 20 min and the P_{sbc} was observed at about 78.90 W
Silva et al. (2002)	The authors determined the η_{therm} of a large-sized solar cooker with TES material. The cooker comprises an FPC, a cooking unity, control valves for HTF, and a storage tank. The HTF was heated inside the FPC and transferred in a thermal siphon circuit, and the regulatory valves directed the HTF flux to the cooking unit and the TES tank to be used later	The results showed the η_{therm} for a varied range of about 34 to 38%
Yadav and Yadav (2013)	The authors investigated an SBC integrated with a PDC and a dual-model TES tank. In the present work, sand was used an SHS material, while acetamide was used as an LHS. After completely charging the SHS/LHS, the cooking was found to be fast-rate cooking	During the off-sunshine hours the T_{wat} was found about 65 °C at 20:00 h
Sethi et al. (2014)	An SBC was designed with a single reflector and integrated this unit into a long-size parallelepiped-shaped cooking pot to be worked efficiently under the cold climatic conditions of Ludhiana city of India	Results of the study showed the FOMs satisfied the standard as per BIS recommendation as 0.16 and 0.54, respectively. For comparability to an orthodox design SBC, the present SBC reduced the cooking time by about 37% with increased cooking power by about 40%
Tesfay et al. (2015)	A solar cooker (integrated with a TES storage tank) was developed for baking Injera under the climatic conditions of Ethiopia. The cooker was large in size and had a cooking vessel of about 50 cm in diameter, which was immersed in the tested PCM (20 kg)	The cooking system successfully achieved the HTF temperature of about 250 °C, which can be retained for about 02 days
Saxena and Karakilcik (2017)	A box cooker was developed to perform under a high thermal storage capacity SHS material by preparing a composite of sand and carbon powder in a specific ratio placed over the cooking tray	The results of experimental work showed that the η_{therm} was about 37.1% while the cooking power was about 44.81 W. The cooker was found to be feasible to keep the food warm at around 21:00 h at night
Maina et al. (2019b)	The author used the groundnut oil as PCM to provide TES to an SBC tested under Maiduguri weather conditions. The results showed a significant enhancement in heat storage compared with an SBC without PCM	The value of the T_{pcm} and energy generated by it was found to be about 137 °C and 307 kJ, respectively, during the off-sunshine hours. The value of F_1 and F_2 was calculated at about 0.13 and 0.4, while the η_{therm} was found to be 32%
Saxena and Agarwal (2018)	The authors enhanced the η_{therm} and convective heat transfer by using a trapezoidal duct into the solar cooker, possibly for forced convection cooking. Results of the experiments showed that the BIS standards were found to a fair agreement with the obtained results	The η_{therm} was found about 45.11%, while the cooking power was estimated about 60.2 W
Verma et al. (2022)	The authors had designed, developed and investigated an SHBC integrated with an SHS material, especially for nocturnal use. In the present work, 02 new performance indicators, such as cooking vessel area fractions for diurnal and nocturnal cooking, were investigated	Results revealed that the SBC's performance increased with a compact mass of TES and improved nocturnal cooking vessel area fraction for 02 kg of cooking substance inside the tested cooker
Servín-Campuzano et al. (2022)	Two different solar cookers, such as Jorhejpaternskua solar stove, had a 3D-CPC, and the second was Tolokatsin solar oven, which had a 2D-CPC furnace. The study is aimed at fabricating such models for the nixtamalization of maize endemic and to examine their cooking performance	The results of the cooking tests showed that the P_{sbc} was estimated about 77 ± 5 W and the η_{therm} was calculated about 27%
Wassie et al. (2022)	The research is aimed at experimentally studying the effect of various reflectors on the SBC's performance. Experiments were conducted without reflectors, with Al foil reflectors, and with mirror-type reflectors on load and without load conditions	The outcome of the study showed that the SBC with 03 side mirror type reflectors was better for cooking efficiency. About 1.5 kg of water was boiled in less than an hour, and F_2 was observed to be 0.533. The efficiency of this model increased by 134% compared with the SBC without a reflector

Table 5 (continued)

Reference	Research work	Results
Tawfik et al. (2022)	This study is aimed at estimating the required TPPs for a box cooker integrated with a tracking-type bottom CPC reflector (TBPR). Paraffin wax was used as TESM. The modified cooker was studied for 02 configurations, such as with and without TBPR	The average estimated COR values for SC1 and SC2 were 0.118 and 0.140 ($m^2 \cdot K$)/W, respectively. The LCCM for SC1 and SC2 were approximately the same, i.e., 0.024 ± 0.0005 $/$M_l$
Aquilanti et al. (2023)	In the present work, a novel design solar cooker shaped like a Newton prism was experimentally studied. It was fabricated with some economical materials. The present model can track the sun through roller coasters. Experiments were conducted to describe its thermal and optical behavior and assess the significance of *Wv*. Therefore, a total of 02 identical models were simultaneously tested (with and without shielding from the wind)	The results showed that both models attained a maximum temperature of about 137 °C during the stagnation test. The shielded cooking system achieved about 90 °C in 02 h for 2 kg of water and about 110 °C in less than 03 h for 02 kg of glycerin
Kumar et al. *(present work)*	*A detachable bed of encapsulated PCM mass is designed and developed to place over the absorber of the tested cooker. Small PCM-filled capsules improved the thermal performance and reduced the cooking times due to enhanced heat transfer inside the cooking chamber*	*The cooker's plate temperature was observed about 150 °C, the η_{therm} was found to be a maximum of about 45.7%, the P_{sbc} was computed maximum of about 54.71 W, the maximum value of "h" was estimated at about 311 W/m °C, and the value of U_{loss} was estimated maximum about 5.71 W/m °C*

Table 6 The cost of different elements of the tested SBC

Elements of present SBC	Total cost ($ USD)
Mirror booster	8.01
Glazing	6.75
Plywood used for fabrication	4.02
PCM bed including paraffin wax	11
Cooking vessels	6.75
Aluminum sheet for laminating the plywood	6.05
Glass-wool	0.60
Miscellaneous (labor, transportation, paint, nails, polish, glue, etc.)	5
Total	$ 48.19 = ₹ 4, 021

PCM-integrated solar energy systems perform better than a conventional design of the same for a long duration. Likely, heat storage materials and techniques provide high thermal stability to the thermal systems, which resulted in improved efficiency with extended hours of performance of the tested systems.

The present system is low in cost and efficient in performing in low ambient conditions. Notably, the current cooker not only cooks almost edibles, but this cooker also can be used for dehydration of foods, milk pasteurization, grain sterilization, wax melting, and sterilization of medical apparatus. These types of solar cookers can be installed in hostels or hospitals for cooking and sterilization processes on a large scale. Likely, cooking systems are required for the remote areas and hilly regions of India so that people can use them for their cooking demands, reduce their biobased fuel consumption, and keep themselves healthy.

Overall, it is a good experimental testing research work that serves as a road map to the study and thermal performance assessment methods, helping the audience to better understand how the data were obtained and the performance assessment, therefore, supporting them in appropriately analyzing its outcomes and focusing towards further scope.

Payback period

The present developed SBC is quite economical for adoption for people of different households due to its low cost and payback period. Table 6 shows the prices of other elements of the present SBC.

After the estimation of the capital cost (*C*) of the present cooker, its payback period has been estimated by the following equation (Saxena et al. 2020).

$$\mathrm{PBP} = \frac{\log\left(\frac{(E-M)}{(a-b)}\right) - \log\left(\frac{(E-M)}{(a-b)} - C\right)}{\log\left(\frac{(1+a)}{(1+b)}\right)} \tag{12}$$

where $C = ₹$ 4,021, annual interest rate $(a) = 6\%$, maintenance charges/anum $(M) = 5\%$ of C, inflation rate $(b) = 5.5\%$, and number of the years $(N) = 05$ years.

In comparison with commonly used cooking fuel, i.e., LPG (which has a cooking efficiency of about 61%, a calorific value of about 45 MJ/kg, and a cost of about ₹61/kg), the PBP for tested SBC is estimated about 3 years and 11 months.

Advantages and limitations

The present model of PCM-based solar cooker has the following advantages.

1. The modified cooker can cook almost edibles.
2. The cooked food is healthy and nutritious.
3. Operation and maintenance are easy.
4. Cooking is fast than a conventional cooker or an SHS-based solar box cooker.
5. Food can be kept warm for around 40 °C inside the cooker for up to 200 min after complete charging of the tested PCM.
6. This cooker can simultaneously cook 02–03 dishes.
7. Continual attention is not required.
8. User-friendly and non-polluting.
9. It can also be used as a conventionally designed cooker by detaching the PCM bed.

It has certain limitations also, as follows.

1. Adequate sunny environment is required for cooking and complete charging of the tested PCM.
2. Cooking is not possible under extremely cold conditions, during rain or any entire night without auxiliary support.
3. Taking a longer time to cook compared with other cooking fuels, such as LPG and electricity.
4. Baking, frying, or deep frying is not possible.
5. Requires a direction change to track the sun about 02–03 about times.
6. Cleaning of glazing, cooking chamber, cooking vessels, and mirror booster is essential before starting cooking every time. Dirty surfaces of these elements can reduce efficiency and extend the cooking time.

No doubt that these limitations have some impacts on the conclusion of the present research work, but the main one is its adoption by people around the world. People would be less interested due to its dependency on climatic conditions. Slow cooking process comparatively to LPG or electricity and cooking load capacity is subjected up to 04 kg only at a single day. Further research is essential to overcome these problems.

Conclusion

In the present work, a simple solar cooker has been designed and fabricated to obtain a better performance enhancement over a conventional designed SBC. For this, a bed of encapsulated PCM mass has been designed and developed to place it over the cooking tray of the present model. Small PCM-filled capsules not only improved the thermal performance but also cut off the cooking times due to enhanced heat transfer inside the cooking chamber. The present cooker has been tested as per standard test conditions especially developed for solar cookers (for stagnation and sensible heating test), and the outcomes have been found for a great range of satisfaction. This PCM bed can be easily attached or detached with the solar cooker, which makes the system user-friendly and easy to operate and maintain.

The results of the present experimental study showed that F_1 and F_2 satisfied the range of recommended values as per the cooking standard. The maximum value of the T_p has been observed about 150 °C, the η_{therm} (instantaneous) has been observed at about 45.7%, the P_{sbc} has been computed at about 54.71 W, the maximum value of the HTC has been estimated at about 311 W/m °C, and the maximum value of U_{loss} has been estimated about 5.71 W/m °C. The total fabricated cost of the cooker is estimated at just approximately $55, which shows a fair possibility of its adoption.

This research work also provides a direction for additional work on the discussed technique. A large-size solar cooker with a cooking capacity of around 12–15 people is under the design process. This cooker will follow the same designed PCM bed but will carry composite PCMs through which the T_{boil} can be achieved in less time, and it will provide an extended thermal storage capacity for evening/night cooking. The cooker can easily track the path of the sun manually due to the roller coasters. Thus, efficiency will be improved more than the present design. Apart from this, however, the present design is sufficient for a small family of 04–05 members to fulfill their cooking needs (who belong to a full sunshine region), but there are some research gaps, such as.

1. A detailed DSC analysis can be done to select a more appropriate PCM for solar cooking.
2. A year-round study is essential to check the appropriateness of the tested heat storage materials.
3. Cost optimization and design optimization are equally important for a wide adoption of the solar cooker for sustainable development.
4. Efficient box cookers are still required for a large-scale cooking.

Besides this, a lower volume of PCM reduces the cooker's performance, while the bulk volume raises the thermal loads, which results in overheating. Therefore, PCM's thermo-physical properties and their complete charging and the discharging process should be well examined. The poor material characteristics of metals significantly affect the performance of box cookers. Lower specific heat, thermal conductivity, and absorptivity reduce the inside heat transfer of a box cooker resulting in a slow cooking process. Thus, a good material selection is necessary for the optimal storage of PCM. Lastly, the cooker should be in the approach of every household, and thus, cost optimization is essential. A good design of cooker with a higher cost is not so useful. So, these are some limitations that should be considered before designing a box cooker.

Nomenclature

SBC: Solar box cooker; *SHBC*: Solar hot box cooker; *BIS*: Bureau of Indian Standard; *PCM*: Phase change material; *PV*: Photovoltaic; *TES*: Thermal energy storage; *LHS*: Latent heat storage; *SHS*: Sensible heat storage; *PBP*: Payback period; *HTF*: Heat transfer fluid; *HTC*: Heat transfer coefficient (W/m^2 °C); *PDC*: Parabolic dish concentrator; *FOM*: Figures of merits; *RCC*: Radiation, conduction, and convection; *T*: Temperature (°C); C_p: Specific heat of the water; *η*: Efficiency of SBC (%); *I*: Solar radiation (W/m^2); *Q*: Net heat gain (W); *h*: Heat transfer; *U*: Overall heat loss coefficient (W/m^2 °C)

Subscript

therm: **Thermal;** *amb*: **Ambient;** *pcm*: **PCM;** *p*: **Cooking plate;** *w*: **Water/cooking fluid;** *l*: **Loss;** *sbc*: **Solar box cooker;** *melt*: **Melting temperature**

Author contribution Avnish Kumar: writing, data curation, and formal analysis.

Abhishek Saxena: concept, writing, review, and editing.

S. D. Pandey: formal analysis, review, and editing.

Arun Gupta: formal analysis, review, and editing.

Data availability All data are given in the manuscript.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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