



Research Article

Performance enhancement of box solar cooker with photovoltaic panel

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ABSTRACT

In developing countries, the energy needed for cooking accounts for approximately 90 % of the total energy consumption in households. A solar cooker is a tool that utilizes the sun's power to heat food and prepare it for consumption. Cooking with the aid of the sun, also known as solar cooking, is a method of preparing food that is typically practiced in settings that prioritize using as little fuel as possible and maintaining good health. The focus of the present study is the inability to perform during the low solar intensity. It is significant for the performance of the solar cooker as it can hamper the motive of using the renewable energy and to conserve the energy used by fossil fuels through solar cookers. It is highly significant for the acceptability of the solar cooker in the society as it is one of the major causes of non-popularization of solar cookers. In the current work, an experimental approach is used in which the construction of a hybrid solar cooker is accomplished by merging the photovoltaic panel and the heater following the design adjustments done in the constructed solar cooker with optimized sidewall inclination to increase the heat intake to the solar cooker. The developed cooker has inclined sidewalls giving the heat to the food vessels from the sides also, which increases the heat given to the food vessel and it is incorporated with the 50 W photovoltaic panels at cover lid and a DC heater placed beneath the absorber plate for giving the auxiliary heat. The use of sidewall inclination with the photovoltaic panel of only 50 watts is rarely observed in the literature. Hence this work of incorporating photovoltaic panel and heater with the inclined side-walled solar cooker is novel for that aspect. Extensive experimental research is carried out on the newly created hybrid cooker, and its performance is evaluated about that of the conventional solar cooker. The maximum temperature achieved in the hybrid cooker during no-load tests is found 25% higher than that of the conventional cooker. The figures of Merit F_1 and F_2 with values 0.11 and 0.63 respectively were also found higher in hybrid solar cooker as compared to conventional solar cooker having values of 0.09 and 0.375 respectively and with few researches found in literature. Even during the month of December, when the solar radiation is as low as 500 W/m², cooking was possible within 120 minutes. The experimental results project new developed hybrid solar cooker to be more efficient than the conventional solar cooker. Performance parameters are also found better as compared to few researches found in literature. Cooking is also possible during low solar radiation which can be useful to make the solar cooker more popular.

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INTRODUCTION

Energy has been an integral component of human life and cannot be separated from it. The availability of energy exerts a beneficial influence on the overall quality of life. The sustained survival and welfare of both individuals and communities are significantly contingent upon the accessibility of energy resources. The strategies of energy conservation and the implementation of renewable energy sources constitute two principal methodologies for energy management and ought to be concurrently embraced. In this regard, it is imperative to initially identify and assess energy consumption patterns across various sectors. According to the report published by the International Energy Agency concerning global energy statistics (2022 Key World Energy Statistics [1]), in the year 2022, residential buildings accounted for 29% of the total consumption of natural gas worldwide. Furthermore, residential buildings utilized 28% of the global electrical energy consumption. In light of this data, Figure 1 illustrates the proportion of the major global sectors consuming the energy for both natural gas and electricity in the year 2022.

As illustrated in Figure 1, residential structures globally constitute the second most energy-intensive sector. This observation has prompted both researchers and corporations to explore various strategies aimed at mitigating the energy requirements of edifices. Nevertheless, the substantial energy utilization of buildings is not the sole issue of concern; energy consumption is also intrinsically linked to the emission of greenhouse gases (GHG). Evidently, diminishing energy utilization in residential structures will exert a considerable impact on worldwide energy consumption and greenhouse gas emissions. Globally, developing nations are typified by low per capita energy consumption, primarily for lighting and cooking; high rates of unemployment in rural areas; a significant reliance on biomass energy sources in rural areas; and a significant disparity in living standards between urban and rural populations [2]. Technologies for renewable energy have recently been used as a sustainable

development strategy [3]. It is possible to turn any renewable energy source into electricity, which may then be utilized for heating and cooking, resulting in the reduction of conventional energy utilization. Such renewable sources include Biomass energy, wind energy, geothermal energy, small hydro power energy and Solar energy. Renewable sources of power, such as those derived from the sun and the wind, have become increasingly popular over the last few decades. Solar energy is the most practical and advantageous kind of renewable energy source since it can be turned into a broad variety of different forms of energy both directly and indirectly. This makes solar energy the most effective and useful form of renewable energy source that has a negligible impact on the surrounding ecosystem. The radiant energy that the sun produces is known as solar energy. Kumar and Ramakrishnan [4] presented several significant outcomes regarding the role and advancements of solar thermal systems (STS) in domestic applications. Solar cookers are gadgets that harness the radiant energy of the sun to cook food. One of the important uses of solar energy is solar cooking, which can take the place of traditional cooking methods. Solar cooking is a well-established technology that is used to cook food in situations where maintaining a healthy diet is of utmost importance. It contributes to the reduction of deforestation as well as the usage of fuel, both of which are growing more expensive as time goes on. Cooking by solar cooker also helps in 17 SDG (Sustainable Development Goals) as per the policy of the United Nations [5]. Dewangan [6] outlined the current status and future possibilities for solar box cookers, focusing on their practical utility, performance parameters, design improvements, social acceptance, and the application of computational techniques to enhance their development. The efficient outcome for setting up a solar energy plant in a Turkish hamlet was determined by Taner and Dalkilic's [7] feasibility study of solar energy-technoeconomic analysis.

Various classifications for solar cookers may exist based on the research methodology. They fall into two primary

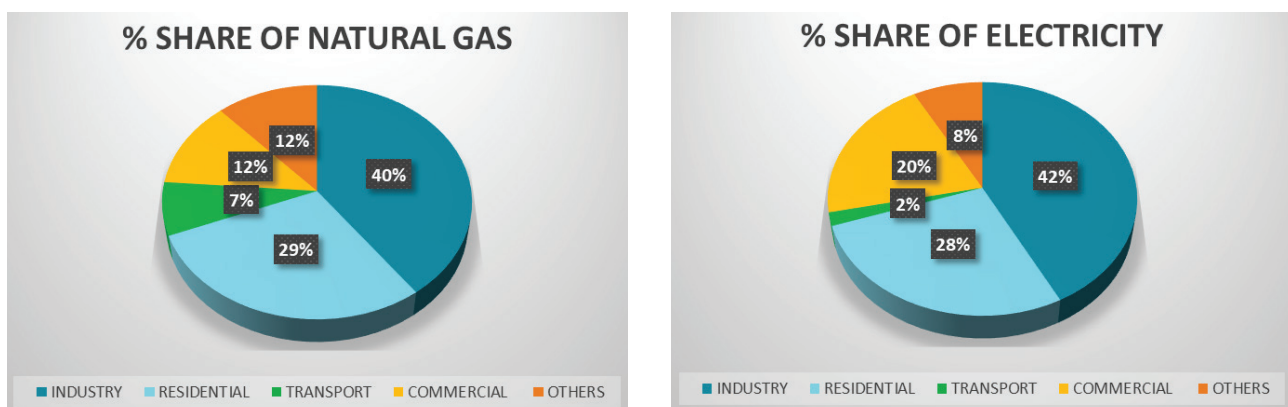


Figure 1. Share of major sectors consuming energy in the total global energy consumption from energy sources like natural gas and electricity in the year 2022 [1].

Table 1. Advantages and disadvantages of Different solar cookers

Type of Solar Cooker	Advantages	Limitations
Box Cooker	• Can cook multiple dishes at once. • Easy to build and use. • Good for slow cooking.	• Requires direct sunlight for effective cooking. • Bulky and may be difficult to transport.
Parabolic Cooker	• Cooks' food quickly (high temperatures). • Can be used for frying, grilling, and baking.	• Requires precise alignment with the sun. • Can be dangerous due to high temperatures.
Panel Cooker	• Lightweight and portable. • Relatively inexpensive to make. • Good for small quantities.	• Slow cooking times. • Less efficient in cloudy weather.
Concentrating Cooker	• Can achieve high temperatures for grilling and baking. • More stable than parabolic cookers.	• Requires consistent sunlight. • Can only cook small quantities at once.

categories: direct and indirect, depending on how solar thermal energy is transmitted to the cooking vessel [8]. Alternatively, there are four primary types of cookers when it comes to the device's configuration: box cooker, concentrating cooker, and panel cooker [9,10]. The advantages and limitations of different type of solar cookers are shown in the table 1.

Looking to the benefits available from the solar cookers, Yettou [11] provided critical insights into the thermal performance and efficiency of parabolic solar cookers in Algeria, emphasizing the importance of regional and seasonal factors in their adoption and use for solar cooking applications.

From the literature, it is found that researchers have worked on various aspects related to the solar cookers namely Mathematical modeling and computational analysis [12–19], Design modifications in solar cooker by [20–28] and by using phase change materials [29–37].

From the review of literature on mathematical modeling and design modifications of solar cookers, it is observed that only one of the models have considered the effect of the thermal contact resistance (TCR) between the absorber plate and the food vessel used to cook the food in the solar cooker which is given by Vaidya and Channiwala[19]. Also, from the literature of different design modifications, it is found that only few design modifications increase the solar insolation available for cooking apart from direct solar incidence. Though different designs and modifications are done in the solar cookers, the major drawback for the solar cooker is its inability to perform in the cloudy day when the solar insolation is less.

Various researchers have carried out experiments on solar cooker for improvement of its performance and analysis by electric back up. Nandwani [38] created an electric cum solar oven that can be used for cooking and baking practically any kind of dish at any time of day or night, regardless of whether solar or electric energy is being utilized. It was comprised of a black-painted electric plate that had a surface area of 0.16 square meters and a wattage of

1500. It was protected by a box made of wood and featured two glass coverings that were spaced apart by 2 cm. The thermostat had a range of 121 °C to 204 °C, which was used to adjust the temperature. Hussain et al. [39] developed a box-type cooker equipped with auxiliary heating. They investigated the performance of two distinct solar cookers through a series of trials. One has an outside box made of teak wood, and the other with an outer box made of Tor to supply 900 watts, six electric iron heating elements, each of which is 150 watts, were utilized. In a different configuration, a holder for a bulb was utilized to supply the heat. The diameter of the bulb holder measured 100 cm, while its length measured 20 cm. The bulb holder was outfitted with a 100-watt bulb that was inserted inside. The bulb holder was pierced with holes so that hot air could flow through it. The results of the first cooker's F_1 and F_2 measurements were found to be 0.16 and 0.27 respectively, whereas the results of the second cooker's F_1 and F_2 measurements were 0.17 and 0.32 respectively. On November 14, 1994, the highest temperature that could be achieved was 90 °C in cooker 1, and 45 °C in cooker 2. Chaudhari [40] estimated the amount of electrical power required by the heater for the solar box type cooker. In his estimation, a power backup of 160 W was plenty for any solar cooker. The natural convective heat transport within a trapezoidal enclosure was investigated by Kumar [41]. The plate was heated by five electrical heaters of the plate type, each measuring 0.38 meters in length and having a total capacity of 250 watts. These were fastened to the bottom of the aluminum tray in order to get consistent heating using an electric power source stabilized by a servo motor. Shehzad [42] designed a sun oven that is circular, electric, and cum. The bottom of the oven consisted of an electric heating plate that was regulated by a timer. The temperature within the oven was maintained by an electric thermostat. The diameter of the plate was 24 inches, and it was protected by an external frame made of wood that had a glass cover at the very top of it. The copper sheet used to make the plate had a 24 gauge.

Mahavar et al. [43] developed a solar cooker that had a backup electric heating system. The outside of the cooker has dimensions of $59 \times 59 \times 23 \text{ cm}^3$. To supply the solar cooker with additional heat, they utilized four Mica sandwich strip heaters, each of which had a power output of 90 W. Both the F_1 and F_2 figures of merit for solar cookers have been determined, and the results show that their values are 0.12 and 0.462 respectively. During the interior testing, they found that the use of electricity for the cooking of a single meal was 0.38 units, but during the outdoor test, it was just 0.18 units, which is less than 50% of the indoor value. Jani and Joshi [44] created a photovoltaic and thermal hybrid solar cooker and gave it the name Improved small-scale solar box type hybrid solar cooker (ISSBH). It weighed 6.5 kilograms and was a solar box-type hybrid cooker. As a backup system, they employed five solar panels, each producing 15 watts, and three rod-type DC heaters, each producing 25 watts. They also provided a battery for use during the night when cooking. In January, the value of F_1 was determined to be 0.087 based on the results of their performance tests on their cooker. The solar panel has dimensions of 0.3 meters by 0.3 meters by 0.005 meters in volume. In the beginning, they supplied a steady operating wattage of 30 watts, however, this was not enough for cooking, so they eventually increased the supply to 50 W.

Thus, with auxiliary heating system, food can be prepared at any time of the year by utilizing either only solar energy (when there is adequate or above-average sunshine), only electric energy (when there is insufficient solar radiation), or a combination of the two types of energy (when there is partial solar radiation). Thus, dependency on the conventional source is reduced. It is expected that with the use of auxiliary energy, when necessary, a solar cooker may be used throughout the year in areas where electricity is available.

From the literature, it is observed that the inability of solar cookers to perform during the low radiation is the main drawback of the solar cookers. It has been addressed in different ways by different researchers by incorporating biomass technology and incorporating electric supply with batteries. This increases the cost of batteries and is difficult to perform in the areas where there is no electric supply. Hence, some better design of solar cooker to increase the solar radiation intake and some source for auxiliary heat supply should be found. Jani and Joshi's [44] solar cooker has an increased weight and price as a result of their use of five photovoltaic panels with a total power supply of seventy-five watts. The use of photovoltaic thermal system is done by many researchers in varied applications [45–47].

Thus, the objective is framed to develop an energy efficient solar cooker with better design, considering the effect of thermal contact resistance between absorber and food vessel and to improve the design of box type solar cooker by incorporating solar panel so as to get benefit of extra heat supply and to reduce operating cost as compared to electric

supply back up. Hence, in the present work, as a novel approach, a hybrid box type solar box-type is designed following Goswami et al. [48] and Vaidya et al. [49], modelled incorporating thermal contact resistance (TCR) as per Vaidya and Channiwala [19] and fabricated with the side walls inclined as per the design modification suggested by Vaidya et al. [26] and further, it incorporates both a solar panel and a heater to reap the benefits of an additional heat supply and achieve the desired level of performance even when there is a lower amount of solar insolation e.g. in December when the global radiation is about 500 W/m^2 . This can benefit the society to popularize the solar cooker and to use the renewable energies for the sustainable development. The performance of the newly constructed hybrid solar cooker with the solar panel is analyzed through the lens of experimentation, and it is compared to that of the conventional cooker.

MATERIALS AND METHODS

This section is divided into two subsections namely (a) Development of Hybrid Solar Cooker and (b) Experimental studies on the developed hybrid solar cooker.

Development of Hybrid Solar Cooker

The methodology chosen is based on a mathematical model given by Vaidya and Channiwala [19]. Calculation of the size of a hybrid solar cooker is carried out considering the energy required to cook the food for a small family as suggested by Goswami et al. [48]. The aluminum plate having the dimensions of the base as $340 \times 340 \text{ mm}^2$ in size and has a depth of 70 mm is used as an absorber plate. The measurement of the plate's top aperture area is $560 \times 580 \text{ mm}^2$.

To attain these dimensions, an aluminum absorber plate is first cut and then bent suitably. The design calls for the side walls to be bent in such a way that they take advantage of the optimal angles as proposed by Vaidya et al. [26]. The surface is prepared by removing dust and contaminants from the surface in a sequential manner. Polishing and buffing are two types of mechanical cleaning processes. Abrasives are utilized during the polishing process in order to remove minute amounts of metal from the surface. The purpose of this step, which comes before buffing, is to create a surface that is free of the larger defects that grinding leaves behind. Following closely behind mechanical cleaning is the use of chemicals to remove pollutants. The pollutants include a wide variety of oils and greases, as well as waxes and organic compounds.

Glass and plastic have traditionally been the go-to options when it comes to solar cooker glazes. The transmittance of the glass is relatively high at around 90 %. The infrared radiation that is released by the hot absorber plate cannot pass through it very easily since it is almost entirely opaque to such radiations. As a result of its availability in very thin sheets, the use of plastic rather than

glass significantly reduces the expense associated with the construction of solar systems. However, exposure to sunshine causes the plastic to depolymerize, which results in it becoming brittle and brown in color. Therefore, the plastic's transmissivity will gradually decrease to a significant level as time goes on. The solar cooker with double glass can reach temperatures between 150 and 250 °C, which is a higher temperature than the solar cooker with a single glass, which means that the amount of time needed for cooking can be reduced. Therefore, there must be two panes of glass in the glazing. There were two pieces of float glass utilized, each measuring 4 mm in thickness, and there was a gap of 15 mm between two pieces of glass. After creating a groove gap in the frame, the inner and outer glass are inserted using epoxy adhesive, and then the assembly is left alone for five to six hours so that the glue may fully cure. Glass frame and housing body are connected together utilizing hinges to complete the connection. The insulation is placed behind the absorber plate as well as all around the absorber plate's perimeter. It prevents heat from escaping via the back and sides of the collector. The material Cerawool, which has a density of 64 kg/m³ and a thermal conductivity of 0.48 W/mK., is utilized for insulation purposes.

The solar cooker's various parts are safely housed in an enclosure that is impervious to the elements. This enclosure prevents moisture, dirt, dust, and air infiltration from entering the collection, which would have a negative impact on the collector's overall performance. Aluminum composite panel is utilized for the exterior body frame because of its low weight and promising lifespan in terms of payback period. Aluminum composite panel is a combination of aluminum and aluminum alloy. The top cover lid of the solar cooker has been outfitted with a foldable solar panel with dimensions of 540 x 540 mm². In conditions with no load, the solar panel has a voltage output of 35 V. Below the absorber plate is a heater that is 340 x 340 mm² in size and operates on 24 V of direct current.

The instrumentation includes photovoltaic panel, thermocouples and D.C. heater. The photovoltaic panel is where the supply comes from for the heater. Thermocouples of the T type are used to measure the mean plate temperature, the temperature of the glass cover, the temperature of the air inside, and the temperature of the food and water that is being cooked. The great sensitivity of 40-50 mv/ °C offered by T type thermocouples makes them the preferred option. The thermocouple undergoes calibration with the ice point serving as its reference junction. In order to determine the average temperature of the outer glass cover in both the loaded and unloaded states, thermocouples have been attached to the inner surface of the outer glass cover with the help of epoxy adhesive. In addition, thermocouples have been attached to the top and bottom of the absorber tray, the side walls of the housing, and the interior of cooking pots.

The standard solar panel has an input rate of around 1000 W/m², however the solar panels now available in the

market achieve an efficiency gain of no more than 15 to 20% at best. Consequently, a 1 m² solar panel will generate between 150 and 200 W when exposed to adequate sunshine. The area of the cover of the designed solar cooker is 600 × 600 m² and the monocrystalline photovoltaic panel of size 580 mm × 535 mm × 3 mm readily available in the market can be fixed on it.

Estimated average global radiation at Surat, Gujarat, India throughout the year for 9 am to 10 am considering clear days is 774.82 W/m². [50,51]

- Considering 17% efficiency, the power available will be 40.87 W ($=0.3103 \text{ m}^2 \times 774.82 \times 0.17$).
- Estimated average global radiation at Surat throughout the year for 12 pm to 1 pm considering clear days is 950 W/m². Power available will be 50.12 W.

Thus, flexible solar panel is applied at the top reflector cover of the solar cooker and the power generated by the photovoltaic panel is given to electrical heater. A flexible solar panel of size 580 × 535 mm² has been placed at the top cover lid of the solar cooker. The solar panel is generating 35.2 V at no load condition. The Specifications of the solar panel are given in Table 2.

Figure 2 shows the Line Diagram of hybrid solar cooker and Figure 3 shows the actual photograph of hybrid solar cooker.

Table 2. Specifications of Solar Panel

Type of Solar Panel	Monocrystalline
Maximum Power ($P_{\max}$)	50 W
Maximum Voltage ($V_{\max}$)	35.2 V
Maximum Current ($I_{\max}$)	1.42 A
Dimensions in mm	580 x 535 x 3
Weight in kg	0.6

STC: Irradiance: 1000W/m², Temperature: 25 °C, AM: 1.5

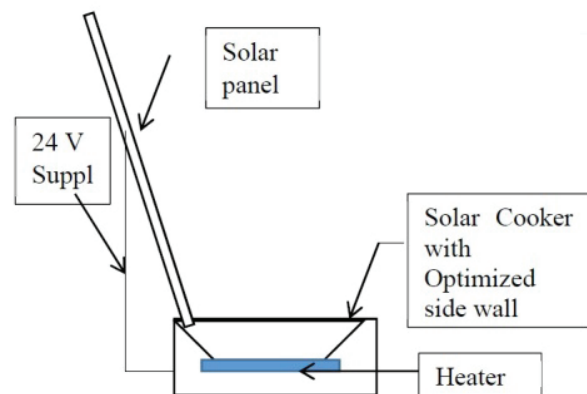


Figure 2. Line Diagram of hybrid solar cooker.

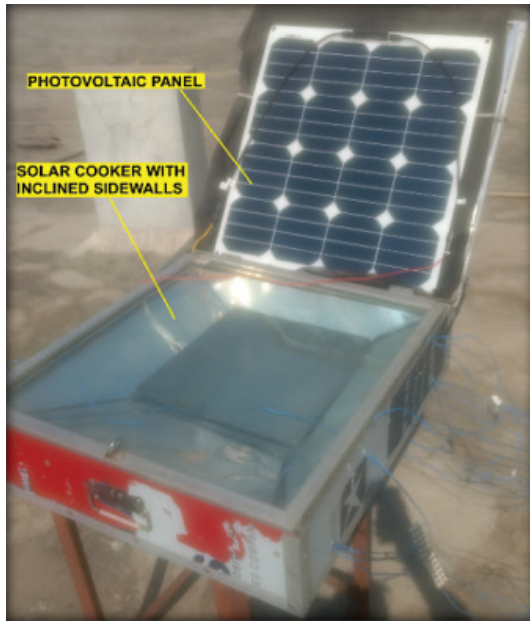


Figure 3. Actual Photograph of Hybrid Solar Cooker.

Experimental Studies on Hybrid Solar Cooker

The details of experiments performed on hybrid solar cooker to assess its performance are given in the Table 3.

Table 3. Details of Experimentation

Sr. No	Date of experiment	Details
1	21-11-18	No load tests with and without heater
2	04-12-18	No load tests. Cooker facing due south
3	17-12-18	No load tests. Cooker facing due south
4	05-12-18	Load tests. Cooker facing due south.
5	10-12-18	Load tests. Cooker facing due south.
6	31-12-18	Cooking tests

Finding out the figure of merit F_1 for no load situations and the figure of merit F_2 for load conditions was one of the ways that thermal performance tests for the newly built solar cooker were carried out [52]. A stagnation test with no load is used to determine the value of the figure of merit F_1 , which represents optical efficiency. This figure of merit is the ratio of optical efficiency to heat loss factor. It is calculated by the equation (1). [52,53]

$$F_1 = \frac{\eta_o}{U_{LS}} = \frac{T_{PS} - T_a}{I_{GS}} \quad (1)$$

Where,

η_o = the optical efficiency,

U_{LS} = the heat loss factor at stagnation

T_{ps} = the stagnation plate temperature ($^{\circ}\text{C}$)

T_a = the plate temperature ($^{\circ}\text{C}$)

I_{GS} = insolation on the horizontal surface at the time the stagnation temperature is reached (W/m^2)

In order to calculate the second figure of merit, F_2 , the solar cooker is left out in the sun with a full load of water and utensils while the reflector is removed from the device. The initial temperature of the water is maintained at temperature of 60°C which is an average between room temperature and the point at which it will boil. Both the water temperature and the sun radiation are recorded until the water temperature reaches 95°C . The figure of merit, F_2 , is calculated using the equation (2). [52,53]

The heat that is delivered to the plate by the heater is also considered in the calculation of F_1 and F_2 for the hybrid cooker, and the total insolation is determined by adding the heat that is received from the sun and the heat that is received from the heater. In the month of December, a cooking test is carried out in order to evaluate the hybrid cooker's capacity for cooking, and the results are compared with those obtained using the conventional cooker.

$$F_2 = \frac{F_1(MC)_w}{A(t_2 - t_1)} X \ln \left\{ \frac{1 - \frac{1}{F_1} \left[\frac{T_{w2} - T_a}{I_G} \right]}{1 - \frac{1}{F_1} \left[\frac{T_{w1} - T_a}{I_G} \right]} \right\} \quad (2)$$

Where,

F_1 is the first figure of merit from the stagnation test;

$(MC)_w$ is the product of mass of water (kg) and specific heat ($\text{J}/^{\circ}\text{C}$)

A is the aperture area of the cooker of the cover plate (m^2);

$t_2 - t_1$ is the time taken for heating from initial water temperature T_{w1} to T_{w2} (sec).

T_a = the average air temperature during the time period $t_2 - t_1$ ($^{\circ}\text{C}$)

I_G = insolation on the horizontal surface during the time period $t_2 - t_1$ (W/m^2).

Figure of merit 2, F_2 , depicts the ability of solar cooker to transform the available heat to the food through cooking vessels.

RESULTS AND DISCUSSION

The newly created hybrid solar cooker was put through a no-load test at first so that researchers could determine what impact the addition of a heater would have on the cooker. Cooking was done on the cooker with the heater connected and without the heater connected on the 21-11-18. The outcomes are presented as below.

Figure 4 demonstrates the fluctuation in temperature of the plate of inclined side-walled solar cooker as a function of time both with and without the heater on 21-11-18. Both curves exhibit a similar trend in the temperature profile, but the maximum temperature that can be achieved with the heater is far higher. It's possible that the additional

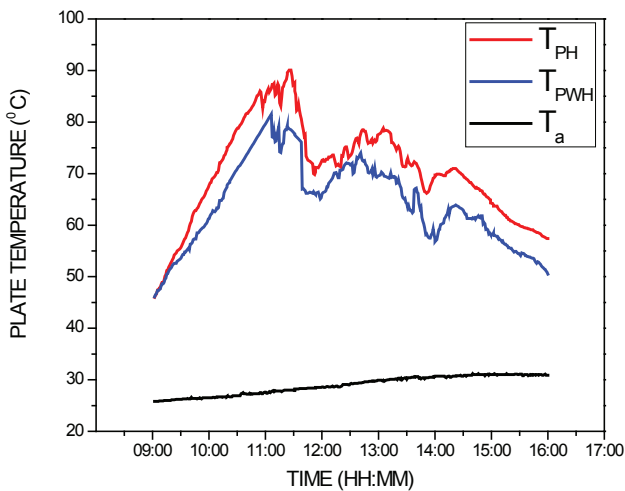


Figure 4. Temperature variation in inclined side-walled solar cooker with heater and without heater effect on 21-11-18.

heat made available by the photovoltaic panel is the reason for this. If the heater is present, it can reach a maximum of around 90 °C, but it can only get to about 82 °C on its own. In addition to this, the temperature decrease in the cooker appears to be less severe when the cooker is equipped with the heater than when it is without the heater. In addition, it has been seen that the starting temperature of the plate is maintained at the same level in both cases, when the solar radiation starts to fall on both the cookers. After 9:30 in the morning, a slow but steady rise in temperature may be noted. This is due to the fact that the solar panel does not have sufficient power for the heater to function at its maximum capacity during the aforementioned hours. As soon as a significant quantity of electricity is created by the photovoltaic panel, the heater is turned on at its maximum

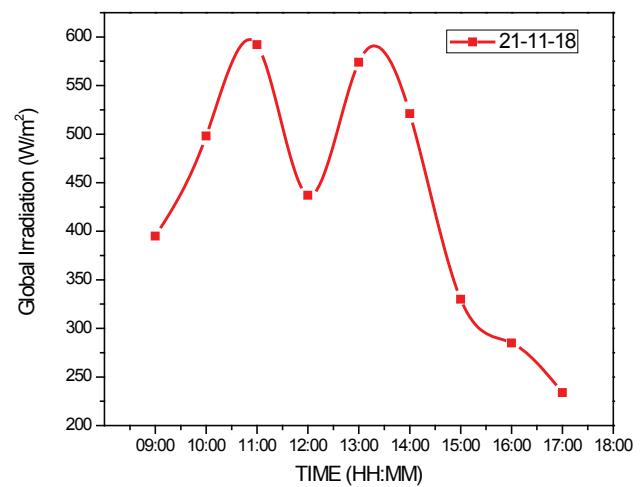


Figure 5. Global Horizontal Irradiation on 21-11-18.

capacity, also known as its highest wattage. This is reflected in the data presented in figure 4 as well. After 1:00 pm, the heater gets heated at full capacity, and as a result, the maximum temperature difference of around 6-7 °C between the two solar cookers is observed until 4:00 pm. Thus, by the auxiliary heating obtained by the photovoltaic panel and the heater, an increase of about 9% is observed in the maximum plate temperature.

Figure 5 shows the Global Horizontal Irradiation (GHI) on 21-11-18. From the figure, it is observed that there is a dip in the values after 11.00 a.m. The variations in the plate temperatures of solar cookers with and without heater may be attributed to these variations in the GHI.

Figure 6 demonstrates the difference in temperature between the plates in the conventional cooker, the hybrid cooker, and the ambient temperature as a function of the local time during no-load test on 4-12-18 and 17-12-18.

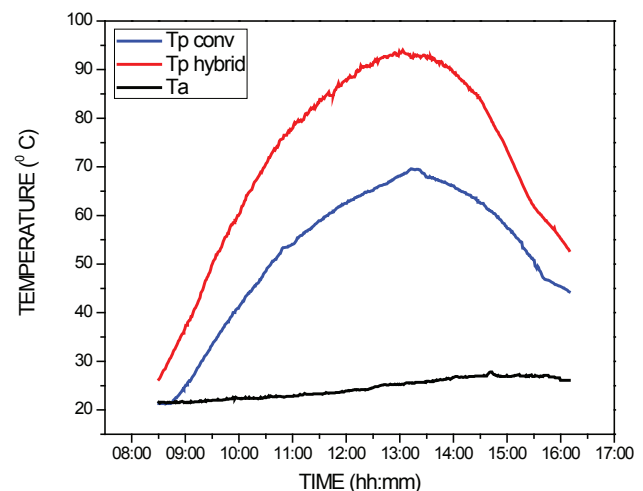
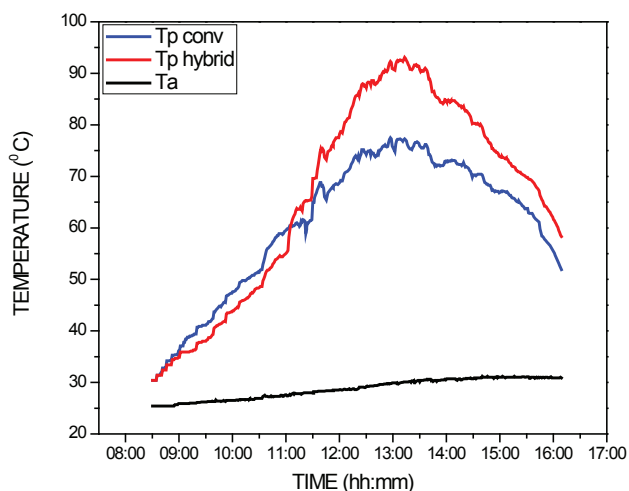


Figure 6. Variation of Plate Temperatures of conventional solar cooker, Hybrid solar cooker and ambient temperature with local time during no-load tests on 4-12-18 and 17-12-18.

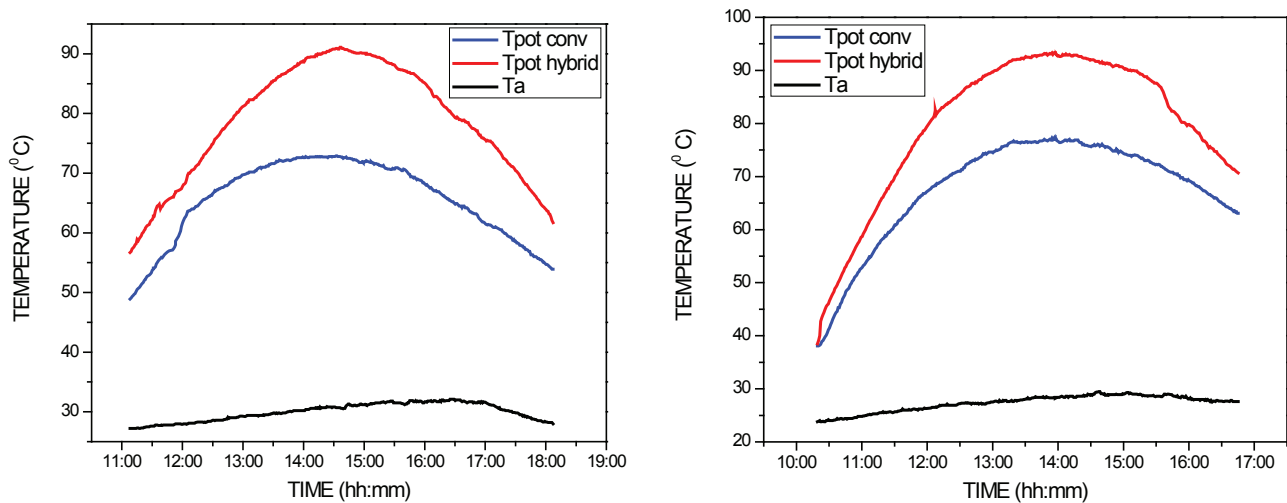


Figure 7. Variation of Pot Temperatures of conventional solar cooker, Hybrid solar cooker and ambient temperature with local time during load tests on 5-12-18 and 10-12-18.

There is a correlation between the passage of time and an increase in temperature, and this correlation is seen in both conventional and hybrid cookers. The hottest part of the day occurs around in the middle of the day and obviously, the peak solar insolation occurs at midday. Additionally, in comparison to a conventional cooker, the temperature that is maintained throughout the day in a hybrid cooker is higher.

The maximum temperature achieved in the hybrid cooker is found 25% higher than that of conventional cooker due to sidewall inclination of the solar cooker and the addition of an auxiliary heating by the DC heater empowered by the photovoltaic panel. Plate temperatures of both cookers reach to their maximum value at nearly 1:00 p.m., but then the rate of reduction in the temperature of hybrid solar cooker is found more which emphasizes the need to retain the heat for more time.

The range of figure of merit, F_1 , that may be estimated from equation (1), for a conventional cooker is 0.07 to 0.10, but the range for the solar cooker having a modified design with photovoltaic panel is 0.096 to 0.12 respectively. The maximum value of 0.10 for a conventional cooker is lower than the maximum value of 0.12 for a newly developed hybrid cooker which justifies the idea of using the photovoltaic panel. The average figure of Merit F_1 is found to be 0.11 for the hybrid cooker and 0.085 for the conventional solar cooker for no load tests.

Figure 7 demonstrates how the temperature of the water-filled pot changed throughout the load test using both a conventional and a hybrid solar cooker on 5-12-18 and 10-12-18. The tests were conducted for six days and the similar trends were observed on all days. In the beginning, the temperatures of pots in both the solar cookers are the same. However, after a short period of time, it is discovered that the temperature of the pot in the hybrid cooker is increasing more than that of the conventional cooker.

Finally, it reaches the maximum value around 14:00 hours in the afternoon. The pot temperature of hybrid cooker is found about 25 % higher during the period of 12:30 pm to 15:00 pm. Also, the maximum value of pot temperature is found to be around 18 °C higher than that of the conventional solar cooker. As a result, the capacity for accumulating heat that a hybrid cooker possesses can be deemed to be greater than that of a conventional cooker.

As calculated from equation (2), the figure of merit, F_2 values that can be achieved with a conventional solar cooker range from 0.3 to 0.45, whereas those that can be achieved with a hybrid cooker range from 0.36 to 0.91. In comparison, the typical value of F_2 for a conventional cooker is 0.375, whereas the value for a hybrid cooker is 0.635.

The results of figure of merit, F_1 and F_2 are summarized and given in Table 2 and Table 3.

Table 2. Summarization of Results for no-load tests

Date of Experimentation	F_1 for Conventional Solar Cooker	F_1 for Hybrid Solar Cooker
04-12-18	0.07	0.096
17-12-18	0.10	0.12
Average	0.09	0.11

Table 3. Summarization of Results for load tests

Date of Experimentation	F_2 for CSC	F_2 for HSC
05-12-18	0.30	0.36
10-12-18	0.45	0.96
Average	0.375	0.635

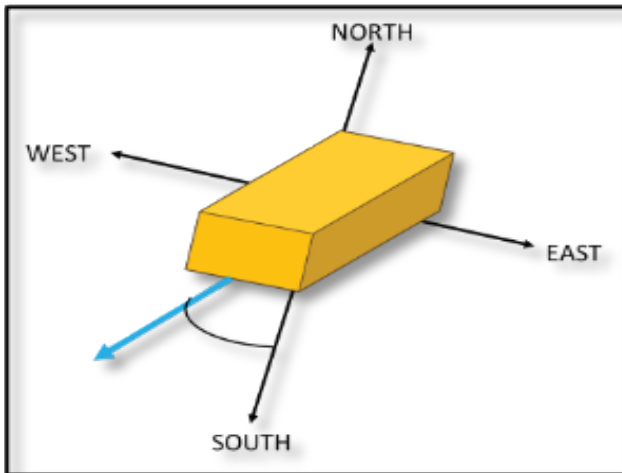


Figure 8. Schematic Diagram showing the direction of Hybrid solar cooker with respect to south direction.

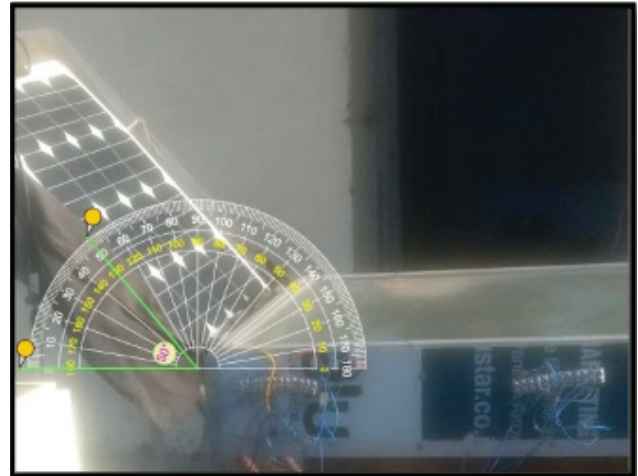


Figure 9. Photographic view of Hybrid solar cooker showing the inclination of photovoltaic panel with the horizontal plane.

Cooking test was carried out on 31-12-2018 on hybrid solar cooker and conventional solar cooker. The direction of both the cookers were kept facing the sun. The surface azimuth angle was calculated to be 34.91° and inclination of the cover with solar panel to be 53.29° with the horizontal surface at 10 am and 18.97° and 49.9° at 1 p.m. [54]. Hence the cooker was placed at 26.94° from south as shown in Figure 8 and 50° inclination was given to the photovoltaic panel as shown in Figure 9.

The cooking test was performed using the hybrid cooker by placing two pots of Moong daal and two pots of Toor daal into the hybrid cooker. Two pots had 200 gm of Moong daal and 350 gm of water in each while other two pots had 200 gm of Toor daal and 350 gm of water in each as calculated from BIS standards[53]. The hybrid cooker was placed with its front facing due south. After the cooking period of



Figure 10. Toor daal and Moong daal placed in the hybrid solar cooker for cooking during experimentation.



(a)



(b)

Figure 11. Toor daal (a) and Moong daal (b) found fully cooked after the cooking period.



Figure 12. Cooked Toor Daal checked and found fully cooked.

panel to enhance the performance of the solar cooker is one of such approaches. The amalgamation of photovoltaic (PV) panels with solar cookers signifies a considerable progression in the realm of solar energy applications, thereby augmenting both culinary efficiency and energy sustainability. This hybrid methodology synergizes the advantages of solar thermal cooking with the electrical output generated by PV systems, thereby facilitating versatile energy utilization within domestic environments. Thus, with an objective to develop an energy efficient solar cooker with better design and performance during the low solar intensity conditions, a hybrid box type solar cooker is designed, developed and integrated with a monocrystalline photovoltaic panel of 50 watt placed at the top cover lid. A DC heater is placed beneath the absorber plate which gets the power supply through the photovoltaic panel. Refereeing the literature available, use of sidewall inclination with the

Table 4. Comparison of similar work from literature

Parameter	Joshi [55]	Mahavar[43]	Present study
Time of study	January	April and July	December
Source of Auxiliary heat supply	Photovoltaic panels	Electric back up supply	Photovoltaic panels
Power supply	75 watts	Power backup of 180 watts	50 watts
Figure of merit F_1	0.087	0.093	0.11
Figure of merit F_2	-	0.462	0.63
Cooking Time	Not mentioned	80 minutes with electric backup of 130-170 watts	120 min
Efficiency η	30% (SSBH model)	-	31.5%

120 minutes, both Toor daal and Moong daal were found to be fully cooked.

Figure 10 shows the pots of Toor daal and Moong daal placed in the hybrid solar cooker for cooking during the experimentation. Figure 11 shows the Toor daal and Moong daal found fully cooked after the cooking period. Figure 12 shows the condition of Toor daal after conforming that it is fully cooked.

Table 4 shows the comparison of results with the similar research work of Mahavar and Joshi with the present study.

CONCLUSION

With the anticipated high demand for energy to be utilized in cooking, it is currently highly relevant to make improvements to cooking devices based on the application of solar energy by which reduction in CO₂ emissions, deforestation and air pollution can be achieved. The focus of the present study is the inability of the solar cookers to perform during low solar intensity. Newer approaches for making solar cookers usable in the low intensity of sunlight are necessary to advance the technology. Use of photovoltaic

photovoltaic panel of only 50 watts is not observed. Hence this work of incorporating photovoltaic panel and heater with the inclined side-walled solar cooker is novel for that aspect. No-load tests, load tests and cooking test were carried out for the performance of the newly developed hybrid solar cooker.

Main findings of the present study can be summarized as below

- There is an increase of 9% in the maximum plate temperature of inclined side-walled solar cooker with the addition of auxiliary heating operated by solar panel.
- The temperatures of the plates that are achieved in the newly developed hybrid solar cooker are found to be greater by 25% than those that are achieved in the conventional cooker.
- The figure of merit F_1 for the hybrid solar cooker, which was acquired during the stagnation test, is discovered to be higher throughout the day than that of the conventional cooker. The average F_1 for conventional solar cookers is 0.09, whereas the average F_1 for hybrid cookers is 0.11. The value of F_1 is also found higher than that of Joshi & Jani and Mahavar et.al.

- During the load testing, the average figure of merit F_2 for the hybrid cooker was found to be 0.635, whereas the average figure of merit F_2 for the conventional cooker was found to be 0.375. It is also found higher than that of Mahavar et. al.
- Cooking tests performed on the hybrid and conventional cookers depict that food is found fully cooked in the newly developed hybrid solar cooker after the cooking time of 120 minutes. This suggests that the newly developed hybrid cooker can also be used even during December when the average solar intensity is around 500 W/m^2 or even less, with the help of the heat input by the heater which is available due to the solar panel.

Thus, the experimental results project new developed hybrid solar cooker to be more efficient than the conventional solar cooker.

Future research work may be focused to integrate solar cookers with various renewable resources together such as thermal, photovoltaic panels, biomass etc., to get an increase in the heat input. The use of various nanomaterials in combination of hybrid solar cookers can be done for better heat accumulation. For heat retention, the hybrid cookers may be integrated with different energy storage materials. Improvements in the design, materials used to construct solar cookers, insulating materials, reflective materials etc. can be focused. The design and performance of solar box cookers can be optimized through the use of a variety of computational techniques, such as computational fluid dynamics (CFD) and Artificial Intelligence Things (IoT). These methods provide novel approaches to evaluating and enhancing solar box cooker efficiency, opening the door for further developments in solar cooking technology.

NOMENCLATURE

A_p	Aperture area of the cooker of the cover plate (m^2)
F_1	The figure of Merit 1 from the stagnation test
F_2	The figure of Merit 2 from the load test
I_{GS}	Insolation on the horizontal surface when the stagnation temperature is reached (W/m^2)
U_{LS}	Heat loss factor at stagnation
T_{PS}	Stagnation plate temperature ($^{\circ}\text{C}$)
$t_2 - t_1$	Time taken for heating from T_{w1} to T_{w2} (s).
T_a	Ambient temperature ($^{\circ}\text{C}$)
MC_w	Heat Capacity of water ($\text{J/}^{\circ}\text{C}$)
T_{pH}	Plate temperature with heater ($^{\circ}\text{C}$)
T_{pWH}	Plate temperature without heater ($^{\circ}\text{C}$)
$T_{p \text{ Conv}}$	Plate temperature for conventional solar cooker. ($^{\circ}\text{C}$)
$T_{p \text{ hybrid}}$	Plate temperature for hybrid solar cooker. ($^{\circ}\text{C}$)
$T_{pot \text{ Conv}}$	Temperature of Pot in the conventional solar cooker ($^{\circ}\text{C}$)
$T_{pot \text{ hybrid}}$	Temperature of Pot in hybrid solar cooker ($^{\circ}\text{C}$)

Greek Letters

ε	Emissivity of the material
η_o	Optical efficiency

Abbreviations

TCR	Thermal Contact Resistance
GHI	Global Horizontal Irradiation (W/m^2)

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

Authors confirm that the data that supports the findings of this study are available within the article. The raw data that supports the findings of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare 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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