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State of the art of solar cooking: An overview

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ABSTRACT

Cooking is the prime requirement for people all over the world. It accounts for a major share of energy consumption in developing countries. Solar energy is contributing major energy requirements of the world's population particularly in developing countries. Among the different energy end uses, energy for cooking is one of the basic and dominant end uses in developing countries. There are number of solar energy based cooking appliances has been design, developed and tested for various applications across the globe. In this paper attempt has been made to provide comprehensive view on standard testing approach of solar cooker, energy and exergy analysis approach and economic evolution of different types of solar cooker. Thermal performance of box type and concentration type solar cookers in both laboratories and actual field conditions also rigorously reviewed and presented in this paper.

Contents

1. Introduction

Cooking is prime necessity for all people across the world. Owing to fuel scarcity or highly expensive fuel cooking energy switch by renewable is a burning issue and is discussed widely in the literature. In developing countries, cooking energy requirement is meeting through fuelwood which resulted in deforestation, fuel-wood shortage, increased costs of fuels and adverse environmental effects. Many researchers work out the environmental effects of fossil fuels, sustainable energy consumption, energy efficiency, conservation, and renewable energy sources in rural areas of developing countries [1–9] and concluded that renewable energy resources are important with respect to environmental effects [10].

Many households that depend on fuel-wood have shifted to modern energy carriers like liquefied petroleum gas [11]. In India particularly about, 70% population still residing in rural areas, there is tremendous demand on resources such as fuel wood, agricultural residues and dung cake to meet the fuel requirements for cooking, water heating and space heating (during winter). Dependence on bio-resource to meet the daily requirement of fuel, fodder in rural areas is more than 85% in many rural districts in India [12]. Presently most of states of India are facing serious problems in availability of

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Nomenclature

$\dot{m}_e$	rate of evaporated mass of water (kg s^{-1})
A	intercept area (m^2)
C_p	specific heat (J kg^{-1} K^{-1})
E	energy (J)
h_{fg}	latent heat of evaporation (J kg^{-1})
I	instantaneous solar radiation (J s^{-1} m^{-2})
I_a	average solar radiation from the time period t_1 to t_2 (W m^{-2})
I_a	average solar radiation from the time period t_1 to t_2 (W m^{-2})
I_s	solar insolation
M	mass (kg)
mc_w	product of the mass of water and specific heat (J °C^{-1})
Q	thermal energy (J)
T	time (s)
T	temperature (K)
T_∞	ambient temperature
t_1	time when water reached T_{w1} (°C),
t_2	time when water temperature reached to T_{w2} (°C),
T_p	plate temperature
U_L	heat loss factor

Subscripts

a	ambient
f	final
i	input
o	output
ra	reference ambient
s	sun
sc	solar cooker
w	water

Greek symbols

ε	exergy (J)
η	energy efficiency (%)
ψ	exergy efficiency (%)
η_∞	optical efficiency

essential energy sources, i.e., bio-resource at rural area on account of acute drought.

The suitability of solar energy for decentralized applications makes it an attractive option to supplement or substitute the energy supply from other sources. Solar cooking is the most direct and promising application of solar energy. Solar energy is a promising option capable of being one of the leading energy sources for cooking [13,14].

The sun has become a potentially viable substitute for fuelwood in food preparation in much of the developing world [15]. Solar cooking systems essentially work on a simple rule of converting the light energy into heat energy. Solar cooking can be done by solar cooker and it is the simplest, safest, most convenient way to cook food without consuming fuels or heating up the kitchen. It is practical due to their inherent simplicity and consequent lower cost. Also the food is physically protected from contamination [16]. The use of solar cookers results in appreciable fuel and time savings as well as increased energy security for rural households using commercial fuels [17].

This is the best options to meet cooking energy requirement during holy pilgrimage of HAJJ where several million Muslims from all over the world meet annually in the tent-covered valleys of Arafat and Mina, where they spend about 4 days [17]. This concept inspire

Fig. 1. World largest solar cooker at Mount Abu, Rajasthan [18].

for community cooking where considerable amount of fuel can be easily saved. In account of this world largest solar cooker was established at Prajapita Brahma Kumaris Ishwariya Vishwa Vidyalaya at Mount Abu, Rajasthan (Fig. 1). This installed solar cooker is in position to cook 38,500 meals per day [18].

The adaptation of solar cooker in an urban area depends on various factors specific to a city. But introduction of solar cooking in refugee camps have no difficulties in adapting to the solar cooker [19]. Solar Cooking International claims solar cooking has been or is being introduced in 107 countries [20].

In this paper, comprehensive review on different type of solar cooker has been made. Deign consideration, theoretical and experimental performance, it's energetic and exergetic analysis and economics performance also discussed.

2. Brief history of solar cooker

Before the age of civilization, cooking of food was unknown. People ate food in the condition in which they found it. Solar was first time to heat wafers by Essenes, an early sect of Jews, to create a food source that is extremely healthy for the human body. The first known person to build a box to solar cook food was Horace de Saussure, a Swiss naturalist and published his work in 1767. He cooked fruits in a primitive solar box cooker that reached temperatures of 88 °C. He was the grandfather of solar cooking. In the same era, in India, a British soldier patented a fairly sophisticated solar cooker that looked a lot like the Solar Chef. In 1894, China opened a restaurant in which solar cooked food was served. Present design of solar cooker started evolving in the 1950s. Number of top engineers, scientist and researcher were hired to study different aspects of solar cooking designs. These studies concluded that properly constructed solar cookers not only cooked food thoroughly and nutritiously, but were quite easy to make and use [21]. In 1945 Sri M. K. Ghosh designed a first box type solar cooker as commercial product. Indian scientists, designed and manufactured number of commercial solar ovens and solar reflectors in 1950, but they were not readily accepted, partly because there were still lower-cost alternatives [22].

3. Classification of solar cooker

There are different type of solar cookers have been developed all over the world. However we can broadly categories solar cooker in three different ways as shown in Fig. 2. Further Schwarzer and da Silva [23] classified the solar cookers in four different ways on the basis of type of collector and the place of the cooking. These are

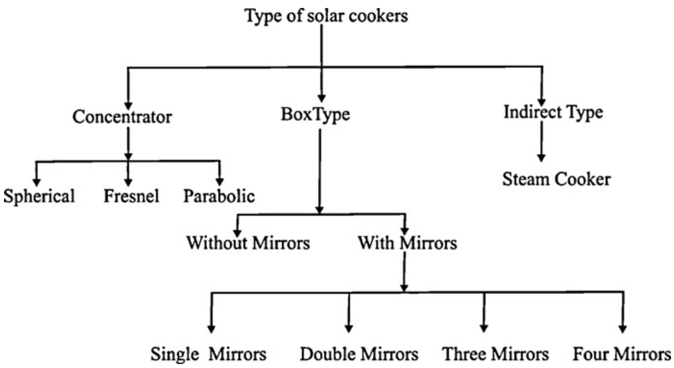

Fig. 2. Classification of solar cookers.

(a) flat plate collector with direct use; (b) flat plate collector with indirect use; (c) parabolic reflector with direct use and (d) Parabolic reflector with indirect use as illustrated in Fig. 3.

4. Design and testing approach

In order to compare the characteristic of different types of solar cookers, power and efficiency to be calculated. The average heating power of a solar cooker can be calculated as follows:

$$\dot{Q}_{\mathrm{heat}} = \frac{m_{\mathrm{w}}.c_{\mathrm{p}}.\Delta T_{\infty-95}}{\Delta T}$$

To avoid the uncertainty of boiling point, heating power is measured from ambient temperature up to 95 °C.

The evaporation power, $\dot{Q}_{\mathrm{e}}$ is estimated during evaporation of water *t* boiling point and it express mathematically

$$\dot{Q}_{\mathrm{e}} = \dot{m}_{\mathrm{e}} h_{\mathrm{fg}}$$

Efficiency is the ratio of power output to incoming power and it express mathematically.

$$\eta = \frac{\dot{Q}}{I_{\mathrm{s}} A}$$

To calculate optical efficiency of solar cooker, heating power of the cooker is considered as power output and it express mathematically.

$$\eta_{\mathrm{o}} = \frac{\dot{Q}_{\mathrm{heat}}}{I_{\mathrm{s}} A}$$

To access the actual performance of box type solar cooker, two figures of merit, i.e., F_1 and F_2 are to be calculated. The first kind of figures of merits F_1, it is the ratio of optical efficiency to the heat loss factor by the bottom absorbing plate and is a measure of the differential temperature gained by the absorbing plate at a particular level of solar insolation. The second figures of merits F_2, is more or less independent of climatic conditions and gives an indication of heat transfer from the absorbing plate to the water in the containers placed on the plate [24].

First figures of merit F_1 is determined by stagnation test at no load conditions and it express mathematically

$$F_1 = \frac{\eta_{\mathrm{o}}}{U_{\mathrm{L}}} = \frac{(T_{\mathrm{P}} - T_{\infty})}{I_{\mathrm{s}}}$$

Second figure of merit (F_2) is to be obtained with full load conditions and is mathematically expressed as:

$$F_2 = \frac{F_1 (mc)_{\mathrm{w}}}{A(t_2 - t_1)} \ln \left[\frac{1 - ((T_{\mathrm{w1}} - T_{\infty})/F_1 I_{\mathrm{a}})}{1 - ((T_{\mathrm{w2}} - T_{\infty})/F_1 I_{\mathrm{a}})} \right]$$

The higher value of factors F_1 and F_2 is desirable for better cooker. The value of temperature T_{w2} should be in the range of 90–95 °C. The initial temperature, T_{w1} can be selected at same value

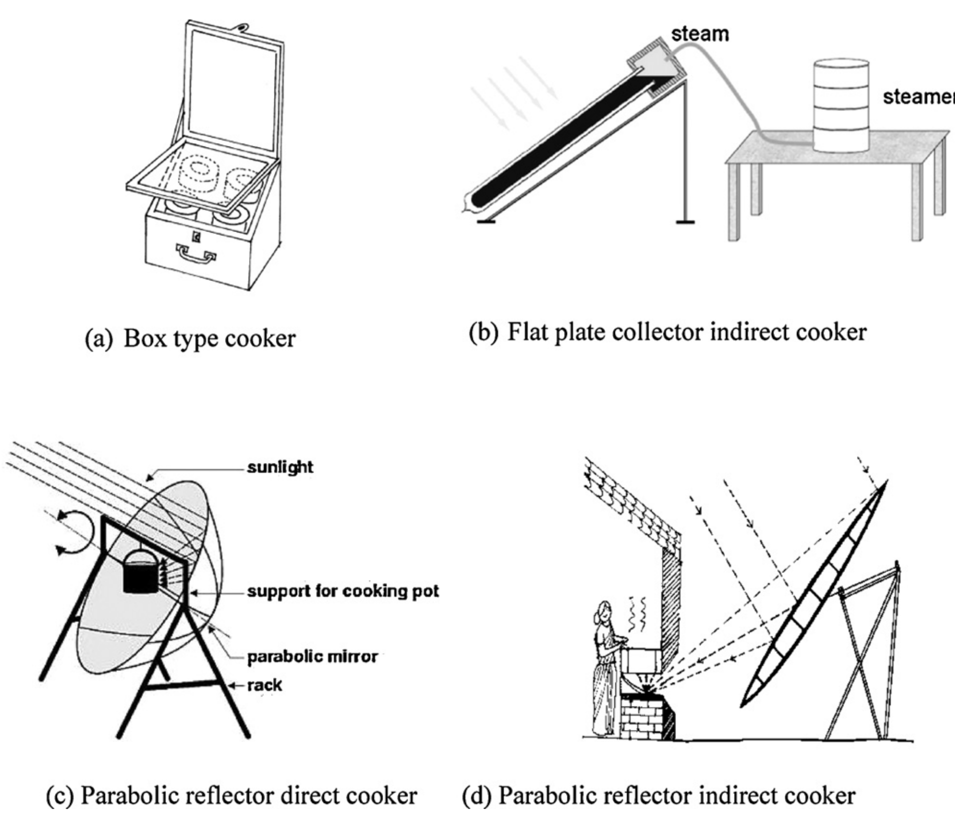

Fig. 3. General type of solar cooker: (a) box type cooker; (b) flat plate collector indirect cooker; (c) parabolic reflector direct cooker and (d) parabolic reflector indirect cooker.

midway between the ambient and the boiling point temperatures [25].

The time that cooker needs to heat an amount of water from ambient temperature to 100 °C, which is also known as standard boiling time t_{boil} [26] is determined as

$$t_{boil} = \frac{F_1(mc)_w}{AF_2} \ln\left[1 - \frac{100 - T_\infty}{F_1 I_s}\right]$$

5. Energy and exergy analysis

5.1. Energy efficiency

Energy analysis based on the First Law of Thermodynamics, i.e., net heat supplied converted in to work. Energy analysis thus ignores reductions of energy potential. Its analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities. Thus, energy analysis is suitable for the sizing and analyzing of the systems using only one form of energy [27]. The energy input to the animal feed solar cooker is energy of solar radiation per unit area of the cooker. The input energy to the cooker can be calculated by following expression:

$$E_i = I_t \cdot t \cdot A_{sc}$$

The energy output of solar cooker can be calculated as follows:

$$E_o = m_w \cdot C_{pw}(T_{wf} - T_{wi})$$

The energy efficiency of animal feed solar cooker is the ration of energy output to the energy input of the cooker and it is calculated as follows:

$$\eta = \frac{E_o}{E_i} = \frac{m_w \cdot C_{pw}(T_{wf} - T_{wi})}{I_t \cdot t \cdot A_{sc}}$$

5.2. Exergy efficiency

The term exergy is defined as the maximum amount of work, which can be produced by a stream or system in a specified environment [28–31]. It is rational efficiency based on the concept of exergy is a true measure of performance of a thermal system. This is based on second law of thermodynamic and the concept of irreversible entropy production [32,33]. It is a useful too for improving the performance of system by determination of the magnitude of energy wastes and losses in system. Exergy analysis involves the examination of the exergy at different points in a series of energy conversion steps, and determination of meaningful efficiencies and of the steps having the largest losses [34]. The overall exergy balance of the solar cooker for the steady-state flow process during a finite time interval can be written as suggested by Ozturk [35].

Exergy input = exergy output + irreversibility

The expression of exergy input to the solar cooker was expressed by Petela [36] which has the widest acceptability, was used to calculate the exergy input.

$$\in_i = I_t \cdot t \left[1 - \frac{4T_a}{3T_s}\right] A_{sc}$$

where T_a is the ambient temperature in K, the sun's black body temperature of 5762 K results in a solar spectrum concentrated primarily in the 0.3–3.0 m wave length [37].

The expression to calculate the exergy output from box type solar cooker, expressed by Ozturk [38] was used to calculate exergy output.

$$\in_o = m_w C_{pw}\left[(T_{wf} - T_{wi}) - T_{ra} \ln \frac{T_{wf}}{T_{wi}}\right]$$

The exergy efficiency for box type solar cooker was obtained by the following relation:

$$\Psi = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\in_o}{\in_i} = \frac{m_w C_{pw}[(T_{wf} - T_{wi}) - T_{rs} \ln(T_{wf}/T_{wi})]}{I_i \cdot t[1 - (4T_a/3T_s)]A_{sc}}$$

Ozturk [39] also suggested the instantaneous exergy efficiency for parabolic solar cooker. It can be defined as the ratio of the increased water exergy to the exergy of the solar radiation:

$$\Psi = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\in_o}{\in_i} = \frac{m_w C_{pw}[(T_{wf} - T_{wi}) - T_{rs} \ln(T_{wf}/T_{wi})]}{I_i \cdot t[1 + (1/3)(T_a/T_s)^4 - (4/3)(T_a/T_s)]A_{sc}}$$

5.3. Box type solar cookers

The box type solar cookers are becoming more popular in many countries. Box type solar cookers are slow to heat up but work satisfactory where there is diffuse radiation, convection heat loss caused by wind, intermittent cloud cover and low ambient temperature [40].

The box-type solar cooker essentially converts solar energy into heat energy which is finally utilized to cook the food stuff kept in the cooker [41]. Optimum temperature is simple box type solar cooker can be achieved around 100 °C at this temperature cooking by boiling is take place [42]. It often accommodates multiple pots. In the Indian context over 639,000 box-type solar cookers have been sold so and the large potential of solar cookers is yet untapped [43]. Hence, solar cooking has a high potential of diffusion in the country, and offers a viable option in the domestic sector [44].

5.4. Parabolic solar cooker

Parabolic concentrating collectors are employed to focus solar radiation where the pot is placed as delineated by Duffle et al. [45], Lof and Fester [46]. Concenrator/point focusing type solar cooker more efficent but frquent adjust is required to maintain point focus. It is type is working on one or two axes of tracking with a concentration ratio up to 50 and temperature up to 200 °C, which is suitable for water boiling and food cooking. The box type solar cooker even with booster mirrors has low concentration ratios (up to 10) and low temperature (up to 100 °C). Therefore, the paraboloid solar cooker is suitable for the types of food that require high temperatures or high rates of cooking [47]. The best known, and probably most effective, solar fryer working on point focusing was developed by Devos [48].

6. Performance analysis

There are number of researcher, scientists and academician involved to promote solar cookers for practical applications and recently significant interest has been seen in the field of design, development and testing of various types of solar cookers like box type [42,49–54], concentrator type [55–58] and oven type [59–62].

From performance point of view every element of a solar cooker has significant importance and direct effects on its performance in any climate conditions [63].

7. Box type solar cooker

The new design of box type solar cooker with a single reflector at the hood to solve the problem of preheating, as faced in the

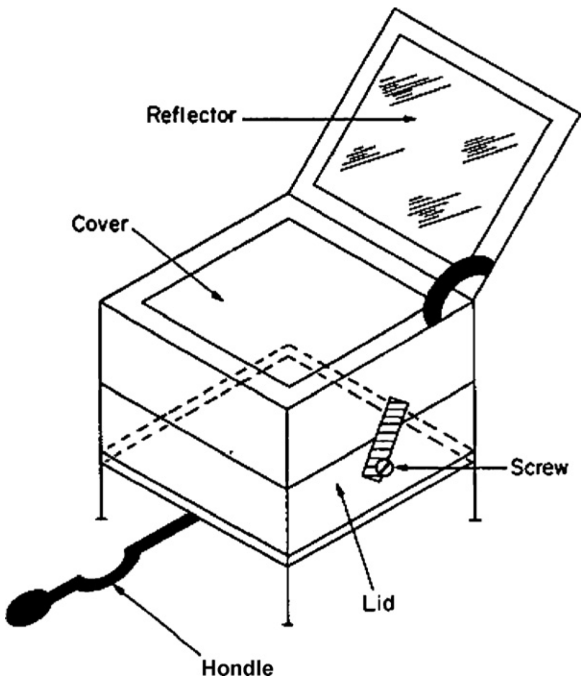

Fig. 4. New box-type solar cooker [64].

Fig. 5. Modified solar cooker with booster mirror [72].

conventional box-type solar cooker was introduced by Tiwari and Yadav [64] as shown in Fig. 4. In this design, the base of the oven acts as the lid, unlike the conventional box type solar cooker and it helps in cooking twice a day. Grupp et al. [65] introduced an advance version of the box type solar cooker. The main advantages over conventional box type cooker is that the pot is fixed in conductive contact to the absorber plate, allowing for better heat transfer and the pot is set into the glazing, allowing access to the pot during cooking while protecting the interior of the cooker.

Pande and Thanvi [66] introduced a new design of SBC that was found more practical in comparison to the simple box cooker. The inner box was designed in a step fashion with a width of 11.5 cm of each step. The cooker was fixed on the flexible iron angle stand to keep the system of optimum tilts in different seasons. It was estimated that the cooker would save 35–40% of the cooking fuel with the use of such type absorber.

Kammen and Lankford evaluated the performance of two box type solar cooker at different solar intensity conditions. First cooker was the Kerr-Cole Eco-cooker assembled from a prefabricated cardboard kit and second model was made of plywood and involved more elaborate construction. During the study it was noted that despite a substantially reduction thermal capacity in the cardboard oven exhibited a maximum temperature and sufficient thermal stability for cooking similar quantities of food to that of the plywood model [67].

Performance evaluation of conventional and Solar Box Cookers International (SBCI) Cardboard solar ovens was carried out in the climate of Costa Rica by Nanswani and Gomes [68]. The test data were taken for 30 different days and it was found that cardboard oven is 15–25% less efficient that the conventional oven. Further they improved SBCI oven and got slightly better performance than the previous SBCI oven. Binark and Turkman carried out the thermal analysis of a hot box solar cooker using the forth order Ranga–Kutta method in Istanbul (Turkey) for a model named ITU-2 with the aim to determine the performance by thermal analysis of any hot box solar cooker at different places and under different conditions. The analysis is independent of numbers of cooking vessels placed in cooker. The theoretical results were reported satisfactorily to experimental results [69].

A box type solar cooker for animal feed preparation was designed, developed and tested by Nahar et al. [70] under Rajasthan climatic conditions to cook 2 kg of animal feed per day. The efficiency of this cooker was reported about 22.6%. The cooker is made of locally available material only glass covers and mild steel absorber plate was purchased from local market. Further Nahar et al. scale up developed animal feed solar cooker to cook 10 kg of animal feed. In continuation Nahar designed, fabricated, tested and compared the performance of a double reflector hot box solar cooker with a transparent insulation material (TIM) with a single reflector hot box solar cooker without TIM [50].

Reddy and Rao [71] showed that the performance of conventional box solar cooker can be improved by better designs of cooking vessels with proper understanding of the heat flow to the material to be cooked. An attempt was made to arrive at a mathematical model to understand the heat flow process to the cooking vessel and thereby to the food to be cooked. The mathematical model considered a double glazed hot box solar cooker loaded with two different types of vessels, kept either on the floor of the cooker or on lugs. It was found experimentally and by modeling that the cooking vessel with a central cylindrical cavity lugs results in higher temperature of the thermic fluid than that of a conventional vessel on the floor or on lugs.

Mirdha and Dhariwal optimized the design of box type solar cooker by introducing booster mirror with the aimed at providing a cooker, which can be fixed on a south facing window (for countries of northern hemisphere, mainly situated near the tropic of Cancer)as shown in Fig. 5. The results of new design was compared with conventional box type solar cooker and it shows clearly that the proposed new cooker can provide higher temperature throughout the day and round the year. It can be used successfully for preparation of two meals in a day and can be used to keep the food warm in late evening Mirdha and Dhariwal [72].

Suharta et al. [73] conduct experiment on three type of Indonesian box type solar cookers: HS 7534, HS 7033 and HS 5521. During the experiment it was found that solar cooker, type HS 7033 gave oven temperature of 202 °C and have a good heat storage capability, therefore they can be used for consecutive cooking.

Ekechukwu and Ugwuoke [52] carried out thermal performance test on box type cooker having plane reflector. They calculated F_1 and F_2 of the solar cooker with and without reflector. F_1 is greater for the cooker having reflector.

El-Sebaif and Aboul-Enein [74] developed a transient mathematical model to access the performance of a box-type solar cooker with a one-step outer reflector hinged at the top of the cooker. The developed model was validated with experimental results in Tanta, Egypt climatic conditions. Good agreement between experimental and theoretical results is observed. The boiling and characteristic boiling times of the cooker are decreased by 50 and 30%, respectively, on using the cooker around midday.

Galip et al. [75] have designed and tested a SBC to track the sun in two axes in the climate conditions of Turkey. It was good to cook only the light meal like rice, eggs, macaroni, etc. A shadow stick on the glazing was used to track the sun. Engine oil was used as thermal storage and opening of the cooker was through side wall as almost in an oven. The obtained values of thermal performance and efficiency were assumed sufficient for the climatic conditions of Turkey.

A simple, efficient solar cooker was designed and its performance in the Egyptian climatic conditions was evaluated by Ibrahim and El-Reidy [76]. The cooker was of the hot box type with a plane booster mirror reflector. The performance of the cooker was measured experimentally for over two years under different working conditions. During the experimental study all kinds of food were cooked including meat, chicken, rice, peas, beans, potatoes, soup, eggs and cakes. A good meal for a family of four was cooked in 3–4 h. It was established that better heat transfer occurred when the cooking pot was covered with an airtight plastic transparent cover rather than using an ordinary metallic cover. The energy balance of the cooker from heat transfer considerations enabled estimates of both oven and food temperature to be made. Calculated values agreed well with the experimental measurements.

Binark and Tudrkmen [69] reported thermal analysis of a hot box solar cooker manufactured at Istanbul Technical University (I.T.U.-2) by using the fourth-order Runge–Kutta method. The results obtained have been given comparatively with the experimental results measured from a cooker. Different foods, including rice, potatoes, eggs and nescafe, have been cooked in 2.5 h with this I.T.U.-2 solar cooker. This cooking period is reasonable in May and June due to the climatic conditions in lstanbul. The cooking is safe and neat. The tastes of the foods are delicious. The results have shown that this solar cooker can be used in many zones of Tiirkiye, especially in Southeastern Anatolia, on condition of improving the construction.

Gaur et al. [77] conduct a study on box type solar cooker with special emphasis on the shape of lid of the utensils used in it. The study revealed that the performance of a solar cooker can be improved if a utensil with a concave shape lid is used instead of a plain lid, generally provided with the solar cooker. The stagnation temperature for a utensil having a concave lid was about 2–7% more than the utensil with a normal lid. The time required for heating the water up to the same temperature in both the utensils was reduced by about 1–13% when a concave shape lid was used.

Solar energy is being used for cooking food and it is derived from the sun. Solar cooker cannot cook when there is insufficient or no sunshine. To overcome this inherent limitation of solar cooker an additional electrical backup has been advised which supplies the cooking energy when necessary. Hussain et al. [78] have discussed the performance of box type cooker by introducing some auxiliary device which will supply electric energy of 100 W to carry out the cooking operation during semi cloudy days of Bangladesh. It is reported that performance of the cooker with auxiliary heating device will be same as that of the cooker without auxiliary device during sunny days if auxiliary device is in off mode. They measured F_1 and F_2 for both the cookers with auxiliary device in off mode in sunny days and found almost same. Chaudhuri [79] estimated the electrical power requirement of a heater for an Indian box type solar cooker considering it's no load figure of merit and energy balance at stagnation. It was found that about 160 W electrical heater is sufficient for cooking.

Fig. 6. Photo of the prototype setup, with pan cover removed [80].

8. Parabolic solar cooker

Concentrating type solar cookers are expected to demonstrate high performance because of the large collection area employed. However, the net amount of heat used is still low. This is greatly attributed to the large amount of heat losses from the bare food pots used. Introducing the oven type concept as an alternative approach for collecting the concentrated solar energy would drastically boost the overall cooker efficiency. In this work, the transient heat balance equations were developed for predicting the thermal behavior of an oven type concentrating solar cooker. This simulation was used to show theoretically the great advantage of using a glass-sided oven over the conventional bare receiver pot. The resulting mathematical model was solved using numerical integration. The transient nature of solar radiation and effects of wind speed variation were all taken into consideration. The analysis showed that the oven type receiving pot has both a higher fluid temperature and overall receiver efficiency compared to the bare receiver type, working under similar conditions.

Kumar et al. designed multipurpose domestic solar cooker/dryer based on a truncated pyramid concept. The truncated pyramid geometry concentrates the incident light radiations towards the bottom and the glazing glass surface on the top facilitates the trapping of energy inside the cooker. The highest plate stagnation temperature, under no-load condition, approached 140 °C and under full-load condition, water temperature inside the cooker reached 98.6 °C in 70 min. Figures of merit, F_1 and F_2, were 0.117 °C m^2/W and 0.467 °C l, respectively. The design was also allows trays to be retained for use as a household dryer [24].

A round year performance of seven different solar cookers under South African climatic conditions by Biermann et al. [13]. The study was conducted in three study areas in South Africa and involved 66 families. The study results reveal that families use solar cookers on 38% of all test days and for 35% of all cooked meals and used wood cooking appliances for 42% of overall test days. Fuel consumption measurements showed overall fuel savings of 38% resulting in estimated payback periods (through monetary fuel savings) from 8 months onwards, depending on the cooker type and region.

A prototype of solar fryer was design, developed and tested with the aim to produce an effective, robust, safe and affordable solar fryer for solar cooking of injera bread by Gallagher [80] as shown in Fig. 6. The proposed design is scalable to any desired pan size. The developed solar fryer is capable of cooking about 30 kg of injera bread per clear day It is assumed that one person consumes 0.2 kg/day hence this is enough for 150 people.

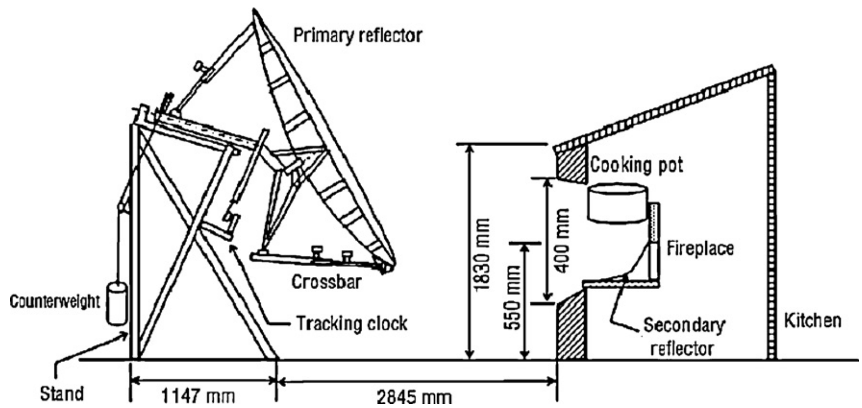

Fig. 7. Community-size solar cooker for indoor cooking [33].

A compound parabolic concentrator (CPC) with reduced gap losses (oversized reflector) was designed and tested by Oommen and Jayaraman [81]. It was found that the instantaneous efficiency of the CPC module is fairly high, even at higher operating temperatures, when compared to a flat plate collector. The potential capacity of the CPC to attain operating temperature higher that the boiling point of water enables it to be used as a low power steam generator.

El-Kassaby [16] developed parabolic square dish type solar cooker. Developed solar cooker can be used for both cooking and distilling water. The feasibility to produce the proposed solar cooker in a commercial scale is quite possible. The efficiency of the present cooker can be increased by around 30% if high temperature black paint is used for the bottom of the pot.

Kalbande et al. designed and fabricated a paraboloidal solar cooker and it was tested under no-load conditions at a recorded maximum temperature of 326 °C. The analysis was made from the sensible heating and cooling curves. The values of the overall heat loss factor (FUL) obtained from the sensible cooling curve were smaller on different days. The minimal heat loss was due to the wind shield provided at the paraboloidal receiver. Analysis of the sensible heating curve gave the values of the optical efficiency factor. The thermal efficiency of the paraboloidal collector was found to be 26% [82].

Concentrating type or direct heating type cookers utilize multifaceted mirrors, Fresnel lenses, or parabolic concentrator to attain higher temperatures. Typically, they heat up quickly and to higher temperature but are not well insulated and require directional adjustment to track the sun. As concentrating cookers primarily utilize direct beam radiation, so high degree of clearness of the reflector is very much essential. It is very difficult to control some of the events which reduce the clearness of the reflector and thereby affect the performance of the cooker. A Fresnel type domestic concentrating cooker, suitable for cooking, frying, preparation of chapattis, etc., was designed and developed by Sonune and Philips [57].

Hosny and Abou-Ziyan designed, constructed and carried out tests to compare the performance of two full tracking solar cookers, namely a paraboloid dish solar cooker (PDSC) and a booster mirror solar box cooker (BMSBC) during a winter season in Cairo under the same operating conditions [83].

Hussein et al. [84] designed, constructed and tested a novel indirect solar cooker with outdoor elliptical cross section, wickless heat-pipes, flat-plate solar collector and integrated indoor PCM thermal storage and cooking unit under actual meteorological conditions of Giza, Egypt.

9. Exergetic analysis

In the beginning exergetic evaluation of low cost parabolic type and box type solar cooker was conducted by Ozturk [39]. Later Petela [85] inspired from Ozturk [39] study and he conducted an experiment on cylindrical trough shape solar cooker to analyzed exergetic performance in actual use. Exergy analysis is a useful tool for evaluating the thermal performance of the cooker. The design parameter optimization of a solar cooker can be made by the exergy analysis. Comparative study on energy and exergy efficiency for Solar Box and parabolic cookers was conducted under Turkey climatic conditions by Oztruk [86].

Kaushik and Gupta [33] compared an energy and exergy efficiency performance of community-size as shown in Fig. 1, and domestic-size paraboloidal solar cooker. During the study it was found that, the community size cooker provides high performance, which is indicated by high energy efficiency, exergy efficiency and low characteristic boiling time in comparison with the domestic size cooker. The low efficiency of these cookers is attributed to the optical and thermal losses from the reflector and pot. The exergy efficiency of any solar cooker or solar thermal device is very low because input solar radiation is rich in exergy and being utilized in the form of heat at low temperature. The exergy efficiency can be increased only marginally by increasing the reflectivity of reflectors, proper designing of cooking place and by using a suitable cooking pot (Fig. 7).

Experimental investigation of energy and exergy efficiency of masonry-type solar cooker to prepare animal feed made of cement,

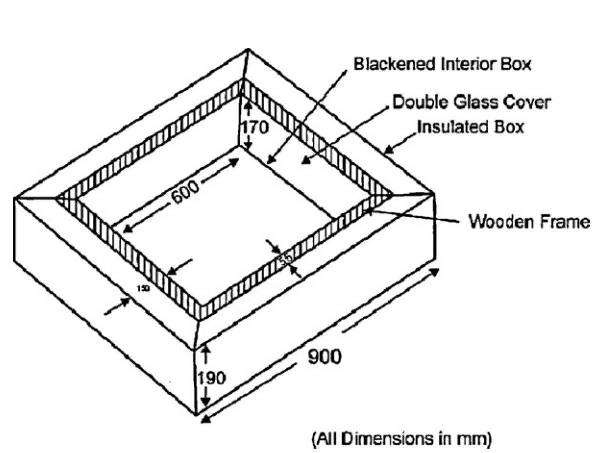

Fig. 8. Animal feed solar cooker [30].

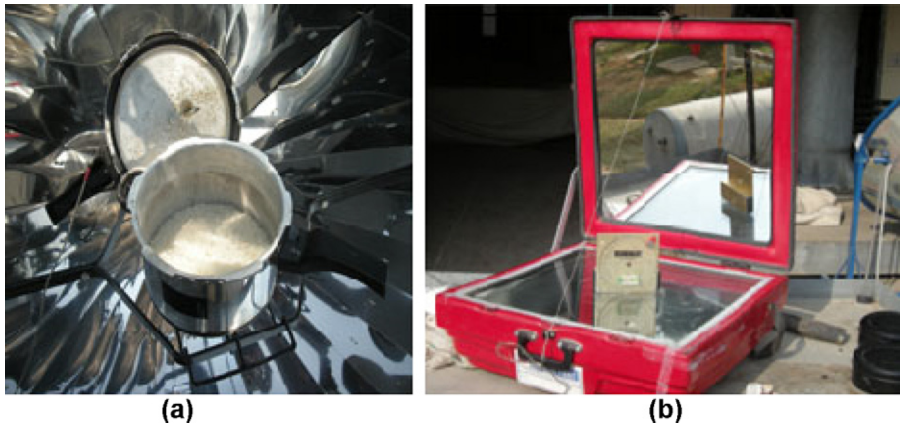

Fig. 9. (a) Paraboloid cooker with food stuff and (b) the photographic view of box-type solar cooker [87].

bricks, glass covers and a mild steel absorber plate as shown in Fig. 8 was evaluated by Panwar et al. [30].

Ozturk has experimentally evaluated the energy and exergy efficiencies of a simple and low cost SBC. The energy output of the SBC ranged from 2.1 to 61.7 kJ whereas the exergy output ranged from 0.4 to 6.2 kJ during the same time interval. The average daily energy and exergy out puts of the SBC were 21.6 and 2.5 kJ, respectively. A linear regression was developed to find the relationships between the energy/exergy outputs, efficiencies and temperature difference. The energy efficiency of the SBC varied between 1.3 and 55.6%, while the exergy efficiency varied between 0.3 and 6% during the same period. The average daily energy and exergy efficiencies of the SBC were 18.3and2.2%, respectively [39].

Petela [85] develop an exergy analysis model of a simple solar parabolic cooker (SPC), of the cylindrical trough shape. The model allowed for theoretical estimation of the energy and exergy losses: unabsorbed insolation, convective and radiative heat transfer to the ambient, and additionally, for the exergy losses: the radiative irreversibilities on the surfaces, and the irreversibility of the useful heat transferred to the water. It was shown that from the energy viewpoint the low efficiency is mainly due to the escape of a large amount of insolation which is not absorbed, and additionally due to the heat loss to the ambient. The exergy efficiency is even lower compared to energy efficiency, mainly due to also the large exergy of the escaping insolation and additionally due to the degradation of the insolation absorbed on the surfaces of the reflector and the cooking pot. The energy efficiency of the SPC is relatively low, e.g., it ranges from 6% to 19% and the exergy efficiency is even lower by about 10 times.

Pandey et al. [87] reported exergy analysis of paraboloid type and box type solar cooker with different food stuff as shown in Fig. 9. It is found that the exergy efficiency increases as the volume of water increases, however, the exergy efficiency of paraboloid solar cooker is found to be higher than that of the box-type solar cooker for all the cases mentioned above. However, it is also found that the exergy efficiency varies with the cooking stuff and water which is due to the fact that the requirement of heating varies with the food stuff.

10. Economic evaluation

Kandpal and Mathur [88] assess the economics of box type solar cookers in the Indian context and it was found that, the price of conventional fuels used for cooking play a decisive role in the use of solar cookers. In rural area particularly people use locally available resources at free of cost (wood, cow dung, agricultural waste, etc.), this is the main cause of poor adaptability in rural areas. They emphasize that solar should be developed at minimum cost with the help of locally available recourses and indigenous technology. Government should provide subsides and apart from subsidies interest free loan to the poor masses for purchasing solar cooker should be granted.

Al-Saad and Jubran [89] develop a low cost clay solar cooker using locally available materials, and needs no skilled labour. The novelty of this new design is that of the solar cooker is the replacement of the absorber plate with locally available black stones. The effects of using the black stones instead of the absorber plate resulted in a solar cooker capable of storing solar energy, hence making late cooking possible.

Nahar et al. execute economic evaluation of animal feed cooker. The fabrication cost of the cooker is only Rs. 1200, which can be recovered in 0.45–1.36 years depending upon the fuel it replaces. The short payback periods reveals that the use of the solar cooker is economically viable. The use of the cooker will save a lot of firewood, cowdung cake and agricultural waste which are presently used for the boiling of animal feed [90].

A novel approach of solar cooker consisting of vacuum-tube collectors with integrated long heat pipes using water as working fluid was reported by Balzar et al. [91]. During the demonstration, high cooking temperatures up to about 250 °C was recorded and it is quite sufficient for frying and baking applications.

Beaumont et al. [92] reported that a family-sized ultra low cost solar cooker with hot box style cooker was designed to be built on site by the users with minimal tools, skills or special materials. It consists of a shallow 1 m^2 square hole in the ground, insulated with straw and lined with adobe (mud and straw), a glass or plastic roof, and a 1 m^2 aluminised plastic reflector with guy ropes for adjustment. An insulated fabric door allows access to the oven; pots are slid in, onto a metal base plate. The cost is about £8. The cooker has been shown to provide cooked food for 10–12 people on clear days with meals around midday and dusk (assuming 0.4 kg dry weight of food per person daily). A 4 l load of water can be brought up to cooking temperature (80 °C) in 60–70 min. The adobe liner provides some thermal mass to even out temperature swings in cloudy weather.

11. Conclusion

Rigorous literature survey on solar cooker, their applications, types, testing approach, energy and exergy analysis, thermal performance and economic of cooker was made. The review gives an overview that the solar cooking is the most direct and convenient application of solar energy. Solar energy is a promising option capable of being one of the leading energy sources for cooking. It is cheap compared with other forms of cooking, and is beneficial for areas with abundant sunshine. Various types of solar cookers are available, out of them box type solar cooker is widely used all over the world. Solar cooker would help in conservation of conventional fuels in rural areas and LPG, kerosene, electricity and coal in the urban areas. Conservation of firewood would help in preserving the ecosystems, and animal dung cake could be used as fertiliser that could aid in increasing production of agricultural products. Moreover, the use of the solar cooker would result in the reduction of the release of CO_2 to the environment [93]. As far as exergy efficiency of both type of cooker is concerned it is even lower compared to energy efficiency, it may be due to large exergy of the escaping insolation and additionally due to the degradation of the insolation absorbed on the surfaces of the reflector and the cooking pot.

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