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Performance characteristics of a new hybrid solar cooker with air duct

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ABSTRACT

A new hybrid solar box cooker (SBC) has been developed and tested for thermal performance evaluation in climatic condition of western Uttar Pradesh, India. The uniqueness of new box cooker is an integrated trapezoidal duct and its other integrated elements. The objective of the study is to enhance the heat transfer rate and to reduce the cooking timings by consumption of minimum heat energy. For this purpose, a 200 W halogen lamp has been placed inside the duct to enhance the heat transfer. Besides this, 450 of small hollow balls of copper have also been used to improve thermal performance of SBC especially on forced convection mode. The performances testing have been carried to evaluate the thermal efficiency, figures of merit (F_1 and F_2), cooking power, heat transfer and overall heat loss coefficient. After completion of experiments, thermal efficiency of SBC has been observed 45.11%, cooking power is estimated to be 60.20 W and overall heat loss coefficient is obtained around 6.01 W/m^2 C. Results shows that the present design follow the BIS standards and can cook almost edibles in poor ambient conditions by consuming only 210 W. Discussion has also been made on the significance of the use of copper balls, fan and halogen lamp over the performance of SBC. The present solar cooker has been found as first kind of SBC which can efficiently perform on forced convection in any type of climatic conditions.

1. Introduction

Cooking is primary need of the people and a major household activity for different households. In India, fuels like; LPG, electricity, kerosene, fuel-wood and dung cakes, are generally used for cooking (Saxena et al., 2013). At present, people from different countries are attracting towards solar energy and using solar applications like; solar cookers, water heaters, solar lights etc. Besides cooking, solar cookers are also having some ecological and economic benefits such as; it saves other conventional fuels used for cooking as well as through solar cooking one can also reduce environmental pollution. Solar cooking has been introduced in 1767 in the world, while in 1876 in India. From 1767 to 2017, numerous designs of solar cookers have been successfully developed by several researchers and pioneers of the field (Saxena et al., 2010a) and some good designs are still in use, around the world. Commonly, there are two types of solar cookers; first one is a solar dish cooker, which is a concentrating type cooker and required a tracking mode for effective cooking. Second is non-concentrating cooker i.e., is a box type solar cooker. A box type cooker is simple in design (construction) and consists of an insulated blackened box carrying two to four cooking utensils, a double or triple glazing and a mirror booster (Saxena et al., 2010a,b). Previous literature on the solar cooking not only show 'the efforts and contribution of researchers' but also present the excellent use of solar energy and importance of solar cookers to save the conventional fuels as well as to keep a pollution free environment.

Besides this, it has been experimentally observed that box cookers have low thermal efficiency in comparison of dish cookers. But, some good methods or techniques are there by which one can easily improve the performance of a SBC, such as; improving the design of cooker or cooking vessel, by using some quality heat storage materials or by making them "hybrid" (a cooker which can perform on dual fuel). Some good designs of cookers (on the basis of attaining maximum T_p in low ambient conditions) are listed in Table 1. It can be seen from previous research works (Table 1) that a lot of research work have been conducted on box type solar cookers to improve the cooking efficiency or cooking power, to minimize heat losses, to reduce the cooking timings and to modify the system for performing during the off sunshine hours by using thermal heat storages or by performing on auxiliary power back up. But, there is no such type of SBC (as the present one) or no research has been conducted on forced convection in previous. This is the uniqueness of the present design of SBC that it can perform on forced convection even in poor ambient conditions or in the night, round the globe. However, Chaudhuri (1999) has been theoretically estimated the electrical backup load for a SBC but some major parameters like; cooker or vessel design, ambient conditions, optimum load range, nature of cooking substance etc., are not shown or discussed in the article.

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Nomenclature

ASAE	American society of agricultural engineers
BIS	Bureau of India standard
F_1	first figure of merit ($m^2\,°C/W$)
F_2	second figure of merit ($m^2\,°C/W$)
h	heat transfer coefficient ($W/m^2\,°C$)
U_L	overall heat loss coefficient ($W/m^2\,°C$)
U_T	top heat loss coefficient ($W/m^2\,°C$)
U_S	side heat loss coefficient ($W/m^2\,°C$)
U_d	duct heat loss coefficient ($W/m^2\,°C$)
U_b	bottom loss coefficient ($W/m^2\,°C$)
P	cooking power (W)
SBC	solar box cooker
TES	thermal energy storage
PCM	phase change material
C/S	cross-section
$\dot{m}$	mass flow (kg/s)
T	temperature (°C)
N	number of cooking vessels
m	mass of the cooking fluid (kg)
C_p	specific heat of cooking fluid (J/kg K)
ΔT	temperature difference between fluid to ambient (°C)
I	solar radiation (W/m^2)
τ_g	glass transmissivity
α_g	absorptivity of the glass
α_v	absorbitivity of the cooking vessel
A, A_{sc}	aperture area of the cooker (m^2)
A_{vb}	surface area of the lid (base) of vessel (m^2)
A_{vs}	surface area of the sides of vessel (m^2)
A_{vwf}	surface area of the vessel walls wetted by the fluid (m^2)
h_{rlug}	radiative heat transfer coefficient from lower to upper glass ($W/m^2\,°C$)
h_{rvlg}	radiative heat transfer coefficient from vessel to lower glass ($W/m^2\,°C$)
h_{rugs}	radiative heat transfer coefficient from upper glass to sky ($W/m^2\,°C$)
h_{rplg}	radiative heat transfer coefficient from absorber to lower glass ($W/m^2\,°C$)
h_{cuga}	convective heat transfer coefficient from upper glass to ambient ($W/m^2\,°C$)
h_{clug}	convective heat transfer coefficient from lower to upper glass ($W/m^2\,°C$)
h_{cealg}	convective heat transfer coefficient from enclosure air to lower glass ($W/m^2\,°C$)
h_{cdea}	convective heat transfer coefficient from duct walls to air enclosure ($W/m^2\,°C$)
h_{cpae}	convective heat transfer coefficient from absorber plate to air enclosure ($W/m^2\,°C$)
h_{cvwea}	convective heat transfer coefficient from lateral vessel walls to enclosure air ($W/m^2\,°C$)
h_{cvf}	convective heat transfer coefficient from vessel to cooking fluid ($W/m^2\,°C$)

Greek letter

η	efficiency

Subscripts

a, amb	ambient
ea	enclosed air
in	input
therm	thermal
w	water
p	plate
lg	lower glass
ug	upper glass
s	sky
p	plate
v	cooking-vessel
f	cooking fluid
diw, dw	duct walls

2. Materials and methodology

In the present work, a SBC has been fabricated by local available materials for thermal performance evaluation. All the experimental testing has been carried out in Moradabad (Latitude is 28°58′N and Longitude is 78°47′E), western Uttar Pradesh. Table 1 shows some novel designs of solar cookers but the present design is quite different from all other available designs in comparison of various aspects like fast cooking response, improved thermal efficiency on forced convection and cooking power etc. The specifications of the present system are shown in Table 2. Followings are some important design considerations for present solar box cooker.

1. A aluminium made trapezoidal duct (commonly used in solar air heaters) has been designed and fabricated as a channel for forced convection. The sheet thickness was 0.2 mm.
2. The length of the duct is around 75 cm (Fig. 2b) and it contains two ends. The small end of the duct is 14 × 14 cm^2 and other end is 1.0 × 51 cm^2.
3. Small end of the duct has been closed while other end is directly connected to the front wall of SBC. For this particular, a small cross section area (1.0 × 51 cm^2) is cut from the front wall of SBC to connect the duct (Fig. 1).
4. A 10 W fan (generally used in air conditioners) has been used for forced convection and placed inside the duct nearby small end at a distance around 10 cm (Fig. 1). It is notable that the small end is completely closed.
5. A halogen lamp (200 W of Phillips™) has been placed inside the duct (Figs. 1 and 2c) to produce a high flux to enhance heat transfer rate inside the solar cooker (discuss in upcoming sections).
6. Apart this, 450 (copper made) hollow balls of 4 mm diameter (approximated) have been placed on the absorber tray of SBC to act like a lug for cooking vessels and improve the heat transfer rate because of higher thermal conductivity (Fig. 1) for fast cooking (Richardson, 1997). The total weight of the balls is 1.98 kg. Although the solid spheres can also be placed but the system will take much time to attain the steady state.

For experimentation, total four different configurations have been developed to the present system. In first case, the system has been tested for stagnation (1st configuration) and sensible testing (2nd configuration) by using copper made balls inside SBC (spread on absorber tray). Testing has been carried out only on natural convection through radiant energy by the sun in first two configurations. In 3rd and 4th configuration, a especially designed duct is used for forced convection and for supplying hot air to the cooking chamber. It is remarkable that a fan and a halogen lamp have been placed inside the duct for enhancing heat transfer rate and to reduce the cooking time. Because the duct has reflective walls from inside, the air inside the system attained a high range of temperature due to high flux generated by halogen lamp that has been placed inside the duct (Fig. 2c). Figs. 1 and 2(a–c) shows the schematic and experimental diagram of the

Table 1
Some novel designs of previous developed hybrid solar box cookers.

Reference	Design	Results
Hussain et al. (1997)	A hybrid SBC integrated with a built-in heating coil (150 W) inside the SBC or a retrofit electric bulb in blackened cylinder	F_1 (0.17) and F_2 (0.32) was found as per standard and cooking was possible in cloudy season
Chaudhuri (1999)	A simple designed SBC with BIS was tested	Electrical load was estimated around 160 W for standard cooking
Oturani et al. (2002)	A modified movable SBC with TES (engine oil) and two reflectors was tested	Cooking efficiency was improved and observed around 42%
Rao and Subramanyam (2003)	A cooking vessel along with lids was designed for improving the heat transfer process to the food. Levitation the vessel by providing a few lugs will make the bottom of the vessel a heat transfer surface	This modification improves the performance of the SBC by improving the heat transfer rates. The times to reach saturation temperature and cooking were remarkably reduced
Nandwani (2007)	A multi-purpose hybrid solar food processor was designed and tested. The electrical energy was not estimated	The effective efficiency was estimated around 24%. The system was feasible for cooking, drying and distillation
Kurt et al. (2008)	Two different models of SBC for rectangular and cylindrical geometries were constructed tested for different load to investigate the effects of box geometries on the cooker performance	The η was observed around 36.98% for the cylindrical model and 28.25% for the rectangular model with reduced cooking time. The cylindrical model was found better
Saxena et al. (2010b)	A BIS standard SBC along with a modified cooking vessel (lugs in a curvature form) was tested to improve heat transfer.	Cooking power was increased up to 79.80 W and cooking time was reduced up to 30 minutes
Misra and Aseri (2011)	The SBC consists of an 8 V, 0.33A DC fan inside the cooker for forced convective environment through a solar PV panel	F_1 and F_2 was found as per standard and cooking time was reduced by 30.6%
Rao et al. (2001)	A conventional SBC was tested for three types of cooking vessels, i.e. conventional vessel, vessel with central annular cavity and vessel with rectangular fins in the central annular cavity (to increase the heat-transfer rate to the cooking vessel)	The hot-air circulation through the annular cavity with fins improves the heat transfer between the water and vessel as well as reduction in cooking times. The cooking vessel placed on lug helps to increase the heat transfer
Saxena et al. (2012)	A simple designed SBC was modified and tested with sand and granular carbon as thermal heat storage mediums	F_1 and F_2 met to standard, cooking time was reduced and SBC was feasible for late hours cooking
Cuce and Cuce (2013)	Two SBCs with ordinary and finned absorber plates were theoretically investigated for thermodynamic performance evaluation	η and η_{ex} of SBCs were plotted versus time for different cases. Some recommendations were made to enhance the power outputs of SBCs
Sethi et al. (2014)	An inclined SBC was tested along with a new designed parallelepiped shaped cooking vessel for improved heat transfer	Figures of merit for the model-1 were estimated as 0.16 & 0.54, respectively. As compared to 0.14 & 0.43 for model-2. 'P' was 37% less and 40% more respectively in parallelepiped shaped cooking vessel of inclined cooker as compared to conventional cooker
Geddam et al. (2015)	A simple designed SBC was tested with two a TES and different cooking vessels for various parameters for optimum load	F_1 and F_2 indicate that the SBC can be used for consecutive cooking on a sunny day for the largest cooking load
Joshi and Jani (2015)	A small capacity hybrid SBC was developed with the help of 75 W of solar PV panel was tested for performance	η of improved IS-SBH was around 38% and estimated cost was around ($120)
Esen (2004)	A solar cooker was integrated with vacuum-tube collectors and heat pipes filled with refrigerant	Three different refrigerants (R-134a, R-407C & R-22) were used along with water inside the system among which R-407C was found more efficient to reduce the cooking times
Sharma et al. (2005)	A prototype solar cooker with evacuated tube solar collector filled with PCM (erythritol)	By using PCM inside the solar cooker, evening cooking was also possible under the climatic conditions of Japan
Hussein et al. (2008)	An indirect type solar cooker with outside elliptical C/S, wickless heat pipes and flat-plate collector which performs on PCM	Magnesium nitrate hexahydrate improves the late hours cooking. The unit can be used for heating or keeping food hot at late night.
Kumar et al. (2010)	A truncated pyramid geometry type non-tracking multipurpose solar cooker	Two figures of merits F_1 and F_2 were estimated for the values 0.117 °C m^2/W and 0.467 °C m^2/W. The design meets to BIS standards for SBC
Panwar et al. (2010)	A masonry animal feed solar cooker made of bricks, glass covers, cement & a mild steel collector plate	The η of cooker varies between 1.12% and 29.78%, and the exergy efficiency varies from 0.07% to 1.52% during the same period
Harmim et al. (2012)	A new box-type solar cooker equipped with an asymmetric compound parabolic concentrator	The experiments conducted in winter and summer seasons, showed a successful performance of a laboratory cooker model. The performance was rated by using the figure of merits, F_1 = 0.1681 and F_2 = 0.35, respectively.
Singh et al. (2014)	A solar cooker with inbuilt TES unit was connected to evacuated tube collector via connecting pipes	Water and engine oil were used as a heat transfer fluid while acetanilide was used as PCM. The cooker was found feasible for cooking in the evening
Soria-Verdugo (2015)	A simple SBC with BIS standards	Study of SBC reveals that the convective coefficients of heat transfer model were as 12 W/m^2 K for absorber to the interior air, 3 W/m^2 K for the interior air and interior wall surfaces and 4.5 W/m^2 K for external convection between the walls and atmosphere
Mahavar et al. (2017)	A solar cum electric cooker has been developed and tested with introducing a new testing parameter for SBC	The cooker was feasible to cook the food within 80 minutes on power back-up (about 170 W)
Saxena and Karakilcik (2017)	A simple SBC with low cost sensible heat storage medium	The experiments conducted in summer seasons, showed a successful cooking program. The performance was rated by using the figure of merits, F_1 = 0.13 and F_2 = 0.44, respectively. Efficiency was found as 37.1%

present system. There is no power consumption in first and second configuration. In third and fourth configuration, total 210 W (200 W of lamp + 10 W of fan operated on A.C. mains) has been consumed for forced convection. This unique feature makes the system 'hybrid' and permits the system for a year round efficient cooking in poor ambient conditions, round the globe.

Apart this, to fix the location of the lamp, a halogen lamp of 100 W has been used and placed inside the duct at different locations from four to five times to attain a maximum fluid temperature. Finally, the lamp is located at around 41 cm from the opening end (i.e., 34 cm away from the cooker's C/S). At this distance, the maximum inside air temperature is noticed around 71.5 °C of SBC during the off sunshine hours, while the temperature inside the duct is around 109 °C. In this configuration some heat losses are observed due to bare surface of the duct. To overcome this problem, the duct has been insulated by a thin elastomeric closed cell foam insulation sheet (generally used in HVAC systems) to minimize the heat losses (Fig. 1). But, still the achieved temperature is not appropriate for a fast cooking response. Therefore, a

Table 2
Specifications of the solar box type cooker (without modification).

Dimensions of outer box	640 × 640 × 200 mm^3
Material for outer casing of SBC	Fibre
Aperture area	485 × 515 mm^2
Glazing	522 × 548 mm^2
Depth of the tray from glazing	80 mm
Emissivity of absorber plate (Al made and blackened)	0.90
Thickness of absorber plate	0.60 mm
Thickness of glass covers	2 mm
Spacing in between glazing (double glazed)	10 mm
Emissivity of the glass	0.91
Insulation	Glass-wool
Thermal conductivity of insulation	0.05 W/m °C
Thickness of insulation from all sides	50 mm
Cooking vessel height (Al made and blackened) and diameter	65 mm and 160 mm
Mirror booster	522 × 548 mm^2

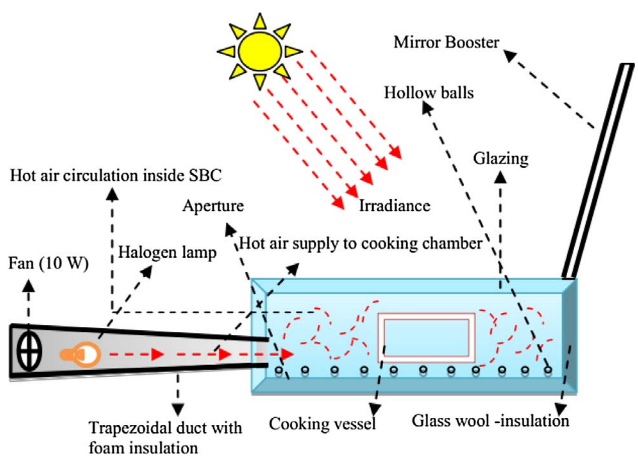

Fig. 1. Schematic diagram of the modified SBC.

200 W halogen lamp was considered for the same purpose. At this time, the maximum inside air temperature is noticed around 111 °C of the SBC during the off sunshine hours, while the temperature inside the duct is around 167 °C. It is notable that the T_{amb} has been noted around 26.1 °C at the same time.

If one can talk about the role of copper balls in present experiments than it is notable that these small balls worked as 'lugs' for cooking vessels in case of natural or forced convection cooking. In natural convection operation, all small copper balls became hot being in contact of direct irradiance and conduction through both the side walls and absorber tray. Apart this, when the cooking vessel is kept on small copper balls, the circulation of hot air between bottom of cooking vessel and the base of SBC improves convective heat transfer to the cooking substance inside cooking vessel, since the effective area by which heat is transferred to the cooking substance has been increased significantly. Therefore, the cooking time is observed to be reduced during the cooking of different edibles (Table 5). The air tightness has also been assessed by measuring water mass before heating and after heating. It has also been observed that there is approximately 16% loss in mass of water due to evaporation in 08 hours duration (from 09:00 am to 05:00 pm).

Overall, following efforts have been made in the present work;

(i) To improve heat transfer rate of the cooking system
(ii) To enhance η of the present cooking device
(iii) To make an efficient solar cooker for cooking in low ambient conditions
(iv) To make an solar cooker for a continuous and un-interrupted cooking
(v) To make an efficient solar cooker for cooking different edibles, round the globe

For experimentation, one kg of fresh water has been considered as a cooking substance. All experiments have been conducted for a stagnation testing (no load condition) and sensible testing (on load condition) for both the configurations of SBC. All the necessary performance parameters such as; thermal efficiency, cooking power, figures of merit, heat transfer coefficient, overall heat loss coefficient has been calculated through experimentation with the help of following equations mentioned in upcoming Section 3 (Saxena et al., 2010a; Garg and Prakash, 2009).

Besides this, variation in temperatures has been measured by using an array of 06 sensors (K-type) thermocouple meter with an accuracy of ± 1 °C. A commonly used device 'Suryamapi' (CEL-201™) with accuracy of 1 W/m^2 has been used to measure irradiance (W/m^2). The wind velocity (m/s) is monitored through an anemometer with accuracy of 1%. The measured variables are recorded at time intervals of 20 min as per ASAE standard (ASAE S580, 2003) (and discussed on an hourly basis of actual reading values). The experiments have been conducted at a fixed flow rate i.e., 0.28 kg/s. All measuring devices/instruments have been checked properly for an error before conduction of experimentation. All experiments have been started at 11:20 h and finished at 13:20 h.

3. Theory and analysis

The schematic diagram (Fig. 3) shows the heat transfer mechanism for hybrid box cooker. They energy balance equations are written for the different components of solar cooker which includes upper and lower glass covers, enclosed air, absorber tray, cooking vessel and cooking fluid. Following assumptions are made for modelling, as follows;

1. Heat capacities of air enclosure, cooking vessel, glass covers and insulation are negligible
2. The components temperatures are uniform but depend upon ambient conditions (i.e., with change in ambient conditions, a change in components temperature is possible)
3. Reflectivity of the glass is neglected
4. Solar irradiance absorbed by the air enclosure and that received by the vessel's wall inside the cooker is negligible
5. No temperature change across the cooking vessel and glass cover
6. There is an identical temperature distribution with in fluid by time 't'.

Energy balance equations for;
For the upper glass

$$I_{in}\alpha_g A_{sc} + (h_{rlug} + h_{clug})\cdot A_{sc}(T_{lg}-T_{ug}) = h_{rugs}\cdot A_{sc}(T_{ug}-T_s) + h_{cuga}\cdot A_{sc}(T_{ug}-T_{amb}) \quad (1)$$

For the lower glass cover

$$I_{in}\tau_g\alpha_g A_{sc} + h_{rplg}(A_{sc}-N\cdot A_{vb})(T_p-T_{lg}) + h_{vlg}\cdot N\cdot(A_{vs}-A_{vb})(T_v-T_{lg}) + h_{cealg}\cdot A_{sc}(T_{ea}-T_{lg}) = (h_{rlug} + h_{clug})\cdot A_{sc}(T_{lg}-T_{ug}) \quad (2)$$

For the enclosed air

$$h_{cdea}\cdot(A_{sc}-N\cdot A_{vb})(T_{dw}-T_{ea}) + h_{cpea}(A_{sc}-N\cdot A_{vb})(T_p-T_{ea}) + h_{cvwea}\cdot N(A_{vs}-A_{vb})(T_v-T_{ea}) = h_{cealg}\cdot A_{sc}(T_{ea}-T_{lg}) \quad (3)$$

For the absorber tray (here, the total aperture area (A_{sc}) is submission of cross-section area of copper ball and area of absorber tray)

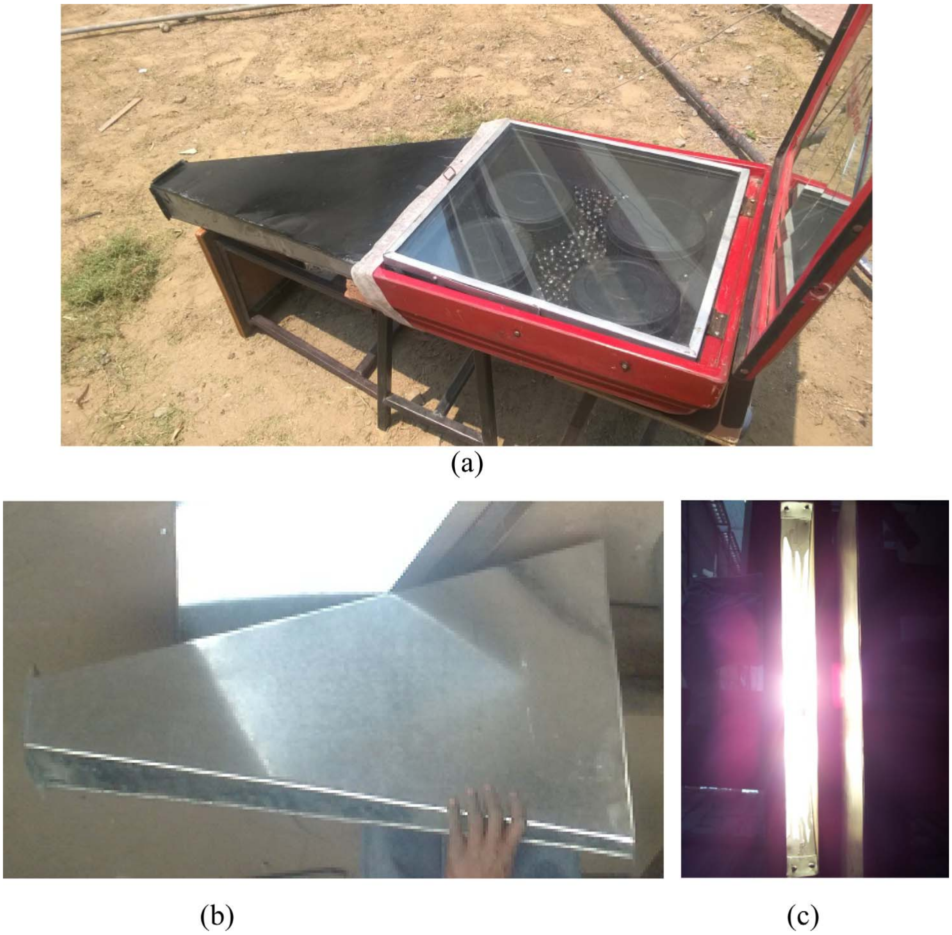

Fig. 2. The SBC and its components (a) experimental set-up, (b) modified duct and (c) halogen lamp inside the duct.

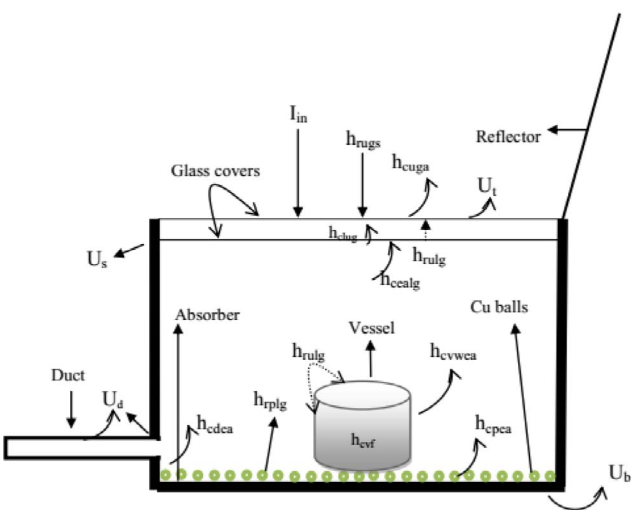

Fig. 3. Heat transfer mechanism of solar cooker.

$$I_{in}\tau_g^2\alpha_p(A_{sc}-N\cdot A_{vb}) = h_{rplg}\cdot(A_{sc}-N\cdot A_{vb})(T_p-T_{g}) + h_{cdea}(A_{sc}-NA_{vb})(T_{dw}-T_{ea}) + h_{cpea}\cdot(A_{sc}-NA_{vs})(T_p-T_{ea}) + U_b\cdot A_{sc}(T_p-T_{amb}) \quad (4)$$

For the cooking vessel

$$I_{in}\tau_g^2\alpha_v A_{vb}N + U_b N\cdot A_{vb}(T_p-T_v) = h_{cvf}\cdot N\cdot A_{vf}(T_v-T_{vf}) + h_{rvlg}\cdot N(A_{vs}-A_{vb})(T_v-T_{g}) + h_{cvwea}\cdot N\cdot(A_{vs}-A_{vb})(T_v-T_{ea}) \quad (5)$$

For the cooking substance

$$h_{cvf}\cdot N\cdot A_{vwf}\cdot(T_v-T_f) = m\cdot C_p\cdot\Delta T \quad (6)$$

After substituting the values of the temperature of glass cover, plate and ambient temperature as per assumptions from Eqs. (1)–(4) in Eq. (5), this can be re-written as

$$\frac{dT_f}{dt} + aT_f = f(t) \quad (7)$$

By using initial condition, $T_f = T_{fo}$ at $t = 0$, Eq. (7) can be re-written as

$$T_f = \frac{\overline{f(t)}}{a}(1-e^{-at}) + T_{f0}e^{-at} \quad (8)$$

[where $\boldsymbol{a}$ is constant and depends on different heat transfer coefficients].

Now, with the help of 1st law of thermodynamics and energy balance equations for the box cooker (Saxena et al., 2010a), energy input can be estimated as:

$$E_{in} = I_{avg}\cdot A_{sc} \quad (9)$$

While, the energy output (on load conditions) for the SBC can be estimated through Eq. (2), as:

$$E_o = \frac{m_w C_{p-w}(T_{wf}-T_{if})}{t} \quad (10)$$

where ‘t’ is the time in seconds to reach final temperature (T_{wf}) from initial temperature (T_{if}), I_{avg} is the value of global solar radiation perpendicular to solar collector and A_{sc} is aperture area of SBC facing the sun (assumed perpendicular in this equation). ‘m_w’ is mass of water in cooking vessel.

Now, having the value of above parameters in Eqs. (9) and (10), one can easily estimate the value of thermal energy efficiency of the present system by:

$$\eta = \frac{m \cdot C_p \cdot \Delta T}{t \cdot I_{avg} \cdot A_{ap}} \tag{11.a}$$

But in the present case, an additional flux (I_L) is available through halogen lamp then Eq. (11.a) becomes

$$\eta = \frac{m \cdot C_p \cdot \Delta T}{t \cdot (I_{avg} + I_L) \cdot A_{ap}} \tag{11.b}$$

Along with this, the cooking power has been estimated by Saxena et al. (2010a):

$$P_{sbc} = m \cdot C_p \frac{(T_{wf} - T_{iw})}{600} \tag{12}$$

Eq. (12) is divided by 600 to account for the number of seconds in each 10 minutes interval as per recommendation (Saxena et al., 2010a).

In case of FPCs, water is working fluid inside the tubes at different temperatures and readings are noted in steady state to obtain the heat loss factor, experimentally. While, in the case of SBC there is no control over the temperature and obviously the operation is in transient state. Once the stagnation is attained, the quasi-steady state is maintained (Mullick et al., 1987). The energy balance for a SBC under no load conditions at quasi-steady state or stagnation is

$$\eta_o \cdot I_{in} = U_L (T_p - T_{amb}) \tag{13}$$

where η_o and U_L are the optical efficiency and the heat loss factor, respectively. These two parameters are desirable for a low value of heat loss and a high optical efficiency for efficient performance of solar cooker and serve as a figure of merit for thermal performance for SBC (Mullick et al., 1987; Tiwari, 2008). This figure of merit is termed as first figure of merit and can be expressed as;

$$F_1 = \frac{\eta_o}{U_L} = \frac{(T_p - T_{amb})}{I_{in}} \tag{14}$$

The second figure of merit can be obtained through the sensible heating test of water up to 100 °C. Assuming the time interval 'dt' is required to raise the temperature 'dT_w' of 'M' mass of water of specific heat capacity 'C_p' and given by;

$$dt = \frac{(m \cdot C_P)'_w \cdot dT_w}{Q_u} \tag{15}$$

where Q_u is the rate of net heat gain by water and $(m \cdot C_p)'_w$ is the heat capacity of the water including cooking vessel. If the 'Q_u' can be defined as net heat gain and 'A' is the cooker surface area and F′ is the heat exchange factor then

$$dt = \frac{(m \cdot C_P)'_w \cdot dT_w}{AF' [\eta_o \cdot I - U_L (T_w - T_a)]} \tag{16}$$

Now, substituting the value of first figure of merit for ratio of η_o / U_L, Eq. (16) can be re-written as;

$$dt = \frac{(mC_P)'_w \cdot dT_w}{A \cdot F' \cdot \eta_o \left[I - \frac{1}{F_1}(T_w - T_a) \right]} \tag{17}$$

Now, assuming the ambient temperature and solar insolation to be constant and the Eq. (17) is integrated over the time 't' which is required to raise the water temperature from T_{w1} to T_{w2}.

$$\Rightarrow \quad t = \frac{-F_1 (m \cdot C_P)'_w}{A \cdot F' \cdot \eta_o} In \frac{\left[I - \frac{1}{F_1}(T_{w2} - T_a) \right]}{\left[I - \frac{1}{F_1}(T_{w1} - T_a) \right]} \tag{18}$$

In the above Eq. (18), the time 't' is not a exclusive property of solar cooker (depends upon ambient conditions-irradiance and ambient temperature) then it can be re-written to obtain the expression for $F'\eta_o$ (a cooker parameter) as follows;

$$F'\eta_o = \frac{F_1 (m \cdot C_P)'_w}{A \cdot t} \text{In} \frac{\left[1 - \frac{1}{F_1} \left(\frac{T_{w1} - T_a}{I} \right) \right]}{\left[1 - \frac{1}{F_1} \left(\frac{T_{w2} - T_a}{I} \right) \right]} \tag{19}$$

However, the value of $F'\eta_o$ can't not be evaluated since the value of $(m \cdot C_P)'_w$ is not known (Mullick et al., 1987). Therefore by introducing the heat capacity ratio (CR = $\{(m \cdot C_P)_w / (m \cdot C_P)'_w\}$ an additional cooker parameter, Eq. (19) can be re-written as;

$$F'\eta_o C_R = \frac{F_1 (m \cdot C_P)_w}{A \cdot t} \text{In} \frac{\left[1 - \frac{1}{F_1} \left(\frac{T_{w1} - T_a}{I} \right) \right]}{\left[1 - \frac{1}{F_1} \left(\frac{T_{w2} - T_a}{I} \right) \right]} = F_2 \tag{20}$$

The value of cooker parameter $F'\eta_o C_R$ can be estimated by Eq. (20) since the heat capacity of cooking substance is known. This new parameter serves as the second figure of merit (F_2) for SBC.

[where T_{wi} is the water temperature at state 1 (at starting), T_{wf} is the water temperature at state 2 (final temperature)]

Now, heat transfer coefficient can be obtained by relationship given by Duffie and Beckman (2012):

$$h = \frac{Q_U}{A_p (T_p - T_f)} = \frac{\tau \cdot I_{avg} \cdot A_p}{A_p (T_p - T_f)} \tag{21}$$

Overall heat loss coefficient has been calculated by using following equation (Channiwala and Doshi, 1989)

$$U_L = \left[\frac{2.8}{\frac{1}{\varepsilon_P} \left(\frac{1}{N_c^{0.025} + \varepsilon_c} - 1 \right)} + 0.825 (x_m)^{0.21} + aV_{win}^b - 0.5 (N_C^{0.95} - 1) \right] (T_{pm} - T_{amb})^{0.2} + \frac{k_i}{t_i} \tag{22}$$

where T_{pm} is the mean plate temperature, N_c is number of glazing, V_{win} is wind velocity, a and b is constant, $\varepsilon_p = 0.85$ and $\varepsilon_c = 0.81$ (Duffie and Beckman, 2012) is emissivity of the plate and glass cover, respectively and k_i is thermal conductivity of insulation (0.041 W/m·K) (Garg and Prakash, 2009) while, t_i is the thickness of insulation.

4. Results and discussion

All the experiments have been conducted in the month of June 2017 on four different sunny days at Moradabad. Water has considered as a cooking substance for load conditions. The set-up has been installed at the place of conduction of experiments at 11:00 h, while the reading is taken from 11:20 to 12:20, after attaining a steady state condition by the system (Mullick et al., 1987). It has been noticed that the present system achieve the maximum temperature (around 12:20 h) after one hour of starting of experimentation (this satisfy BIS standard for solar cookers).

It is also notable that the present system has been kept under observation up to 13:20 to observe thermal behaviour and significance of design parameters over the ambient parameters. After successful completion of experimental testing of new SBC, some edibles have also been cooked in the present solar cooker to monitor the time taken in cooking and for an optimum load range of cooking substance (in kg), which has been shown in Table 5. Although, it is notable that BIS standard has not been developed any standard for hybrid solar box cookers, but in the present investigation two figures of merit (F_1 and F_2) has been considered for testing of the present system.

4.1. Testing of SBC on first configuration

As seen in Fig. 4, on 1st June 2017, the stagnation test (no load condition) has been carried out on first configuration, in which 450 hollow blackened balls (4 mm diameter) of copper are spread on the absorber tray. The system has been placed southward for conduction of experiments at 11:00 h and T_{amb} is notified around 34 °C. The first reading has been taken at 11:20 h and T_{amb} is measured around 37.8 °C at this time, while irradiance is measured to be 710 W/m^2.

At 12:20 h, T_{amb} has been observed 41 °C and T_p is reached up to a maximum value of 136 °C. Irradiance is notified around 810 W/m^2 at that time. The first figure of merit (F_1) has been found within specified standard i.e., 0.12 m^2 °C/W (Kumar et al., 2010). At finishing of experiments (around 13:40 h), T_p is around 122 °C and T_{amb} is 37 °C. The temperatures of the plate of SBC generally increase with incident solar energy per unit inner surface area of SBC. There is heat loss from inner zone of SBC and this is largest in the plate which affects cooking performance directly and drastically. In order to improve the performance and increase the efficiency, one should minimize the losses appropriately.

4.2. Testing of SBC on second configuration

The sensible testing has been carried out on the load conditions (on 02.06.2017), for which 1 kg of fresh water is considered as cooking substance. The water is kept in four similar cooking vessels for an equal quantity i.e., 250 grams in each cooking vessel (total load 1 kg). Again the experiments have been started at 11:00 h, when T_{amb} is around 34.5 °C. The first reading is taken at 11:20 h. At this time T_{amb} and T_p are noticed around 36 °C and 104 °C, respectively and irradiance is observed as 675 W/m^2. In this configuration, T_p is reached up to a maximum value of 143 °C at 12:20 h and T_w has been observed around 97 °C, maximum.

The second figure of merit (F_2) has been estimated for a value of 0.41 m^2 °C/W. Maximum thermal efficiency (η) is notified around 38.1% at 12:20 h. The cooking power of SBC has been estimated for 55.31 W at the same time. Heat transfer coefficient was obtained around 34.51 W/m^2 °C and the overall heat loss coefficient has been estimated 5.10 W/m^2 °C. In the present experiment, minimum value of the temperature of cooking substance has been observed 89.2 °C at 11:00 h, while maximum value is around 97 °C at 12:20 h. It is notable that the minimum value of the hot water is 89.2 °C in the present case which is more than water pasteurization value. Therefore, it can be said that the cooking is safe at this configuration. Figs. 4 and 5 show the performance curves of first and second configuration for stagnation and sensible testing, respectively.

4.3. Testing of SBC on third configuration

Now, for forced convection operation, the present system has been again modified by attaching a trapezoidal duct carrying a lamp of 200 W inside it (Fig. 1). The cooker has been tested on 04.06.17 on the third configuration for stagnation testing i.e., the system is operated on forced convection without any load. The absorber plate carries copper made balls alike in previous experimentations to collect a maximum heat gain from solar energy and to be performed as lugs for cooking vessels. The pre-hot air (around 110.70 °C at T_{amb} = 30 °C) is supplied to the cooking chamber through a special designed duct. The entire system has been properly closed during the experimentation to avoid thermal losses.

As seen in Fig. 6, on 4th June 2017, the stagnation test (no load condition) has been carried out on third configuration for a improve heat transfer rate. The system has been placed southward for conduction of experiments. The first reading is taken at 11:20 h, when T_{amb} is around 37 °C and irradiance has been measured around 705 W/m^2. The duct inside wall temperature is found to be 166 °C. The plate temperature (T_p) and temperature of the enclosed air of SBC are measured around 111 °C and 105 °C, respectively. After one hour (at 12:20 h), T_{amb}, T_p and T_{ea} are noticed to be increased for 39 °C, 132 °C and 114 °C, respectively. The first figure of merit (F_1) is estimated for 0.12 m^2 °C/W. The last reading showed the value of T_p around 122 °C, when the ambient temperature is 34 °C.

4.4. Testing of SBC on fourth configuration

On the next day (05.06.17), the present system has been operated on fourth configuration to perform sensible testing. Experiments are repeated by considering 1 kg of water as a cooking substance (in four cooking vessels for an equal quantity i.e., 250 g in each vessel). The absorber plate carries copper made balls as in previous cases. The pre-hot air (around 111.5 °C) is supplied to the cooking chamber through the duct to enhance heat transfer and cooking efficiency. All small balls achieved a high temperature in comparison of stagnation testing. In this configuration, all the small hot balls of copper generated a current of the hot air inside SBC. The circulation of this hot air remains un-interrupted because a regular supply of the hot air through the duct, which results in enhance cooking efficiency and obviously a reduced cooking time. The heat transfer has been improved through circulation of the hot air inside SBC. The heat energy reached to the cooking substance via conduction to the side walls and bottom of cooking vessel, while directly by convection through the circulation of hot air inside the cooking system and also through solar radiant energy.

The experiments are started at 11:00 h, when T_{amb} is around 31.5 °C.

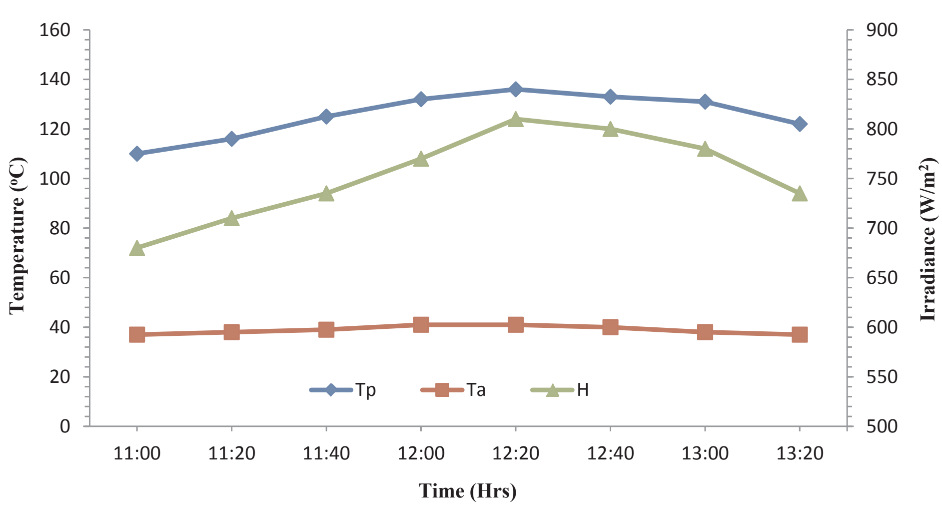

Fig. 4. Stagnation testing of new SBC on configuration 1.

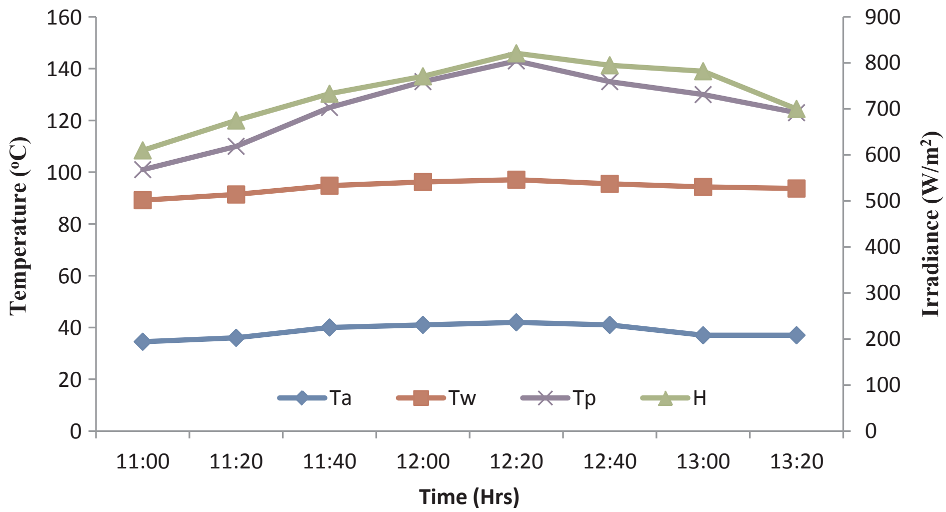

Fig. 5. Sensible testing of new SBC on configuration 2.

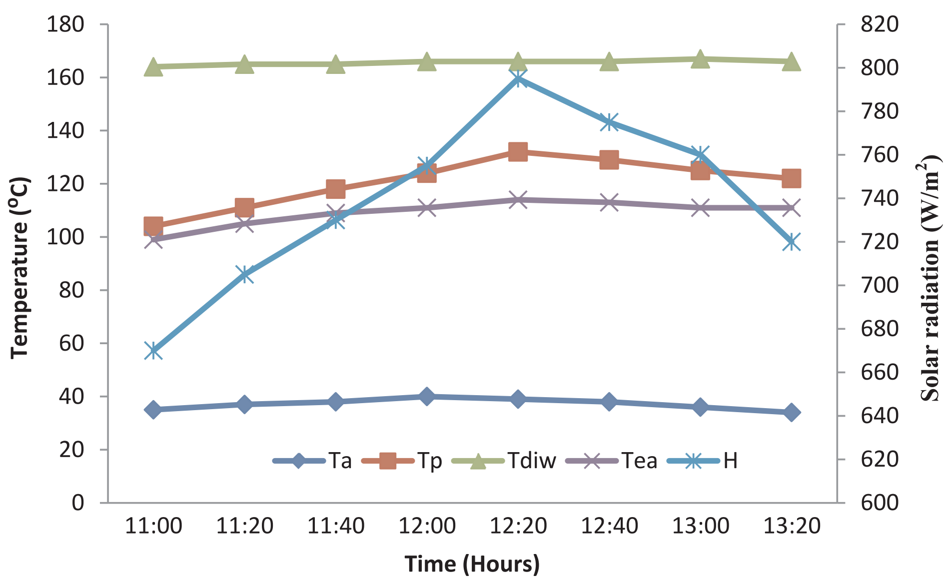

Fig. 6. SBC tested on 04.06.17 on the third configuration for stagnation testing.

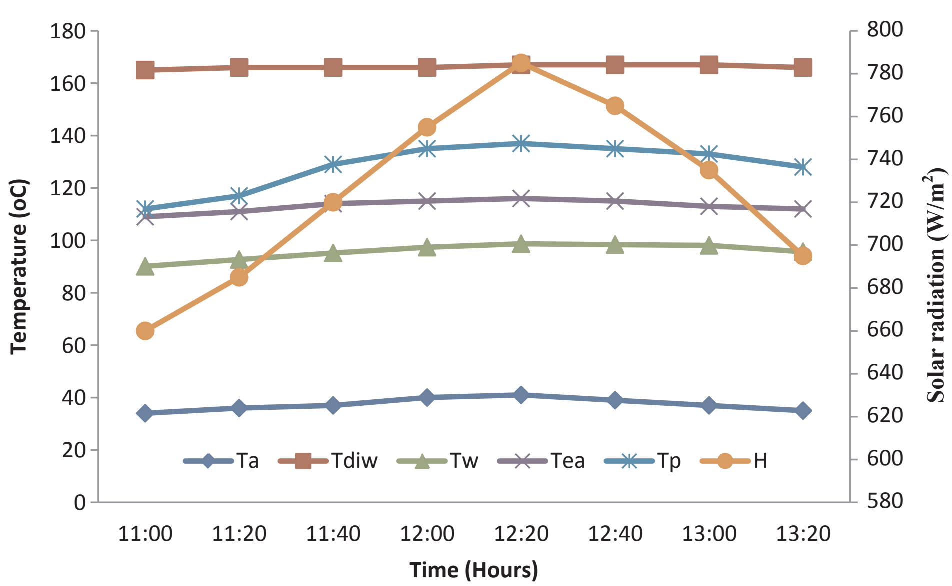

Fig. 7. SBC tested on 05.06.17 on the fourth configuration for thermal load.

The duct inside wall temperature has been found around 165.5 °C. The first reading is taken at 11:20 h when, T_{amb}, T_p, T_w and T_{ea} are around 36 °C, 117 °C, 92.7 °C and 111.5 °C, respectively. The solar irradiance is notified around 685 W/m^2. After one hour, the ambient air temperature and irradiance are reached up 41 °C and 785 W/m^2, respectively, while T_p and T_w are reached up to a maximum value of 137 °C and 98.7 °C, respectively. The second figure of merit (F_2) is estimated for 0.46 m^2 °C/W. Thermal efficiency (η) has been calculated maximum as 45.11% at 12:20 h, while the minimum value is observed 41.9% at starting of the experiments at 11:20 h. The cooking power of SBC is estimated for 60.21 W. Heat transfer coefficient is estimated around 46.86 W/m^2 °C and overall heat loss coefficient is obtained 6.01 W/m^2 °C. In the present experiment, minimum temperature of the cooking substance is observed 90.12 °C at 11:20 h, while maximum temperature is around 98.7 °C at 12:20 h. The temperature of the enclosed air of cooking chamber has been observed around 116 °C (maximum). The last reading shows the value of T_p around 128 °C, when T_{amb} is 35 °C. It is notable that the minimum temperature of the water is 90.1 °C which is better than previous configurations. Figs. 6 and 7 show the performance curves of third and fourth configurations for stagnation and sensible testing.

Apart this, the fourth configuration of present design has been observed better among all the configurations especially in comparison of second configuration (on sensible heating). At the fourth configuration, the efficiency of SBC is found to be improved by more than 7% and heat transfer coefficient is improved for more than 12% over the second configuration. This is because of the duct used for forced convection. The enclosed air increase the heat transfer rate (due to additional flux from the lamp) and provide a better cooking mode by reducing the cooking time. The water temperature has been observed near to be boiling temperature with increased cooking power (60.21 W) of solar cooker on fourth configuration.

Besides this, energy balance equations are solved by preparing a computer program and the estimated parameters has been shown in table 3. The convective and radiative heat transfer coefficients have been estimated with the help of equations presented by El-Sebaii et al. (1994).

Apart this, in order to perform uncertainty analysis of performance parameters, experiments have been repeated on the next day (06.06.2017) from 11:00 to 13:20 h. The uncertainty of different parameters is shown in Table 4. It has been found that the uncertainty at 95% level of confidence was ± 0.96% for thermal efficiency.

After successful experimentation of the present system, the system has been tested for some common edibles by cooking them on different days as well as for optimum load. Table 5 shows the various cooking loads and time taken by the cooker (fourth configuration). It also shows that the present system achieved the boiling temperature in a short span of time with respect to other models as well as feasible to cook a variety of edibles with reduced cooking times. It is notable that previous models of solar cookers (Hussain et al., 1997; Chaudhuri, 1999; Oturani et al., 2002; Rao and Subramanyam, 2003; Nandwani, 2007; Kurt et al., 2008; Misra and Aseri, 2011; Rao et al., 2001; Saxena et al., 2012; Cuce and Cuce, 2013; Sethi et al., 2014; Geddam et al., 2015; Joshi and Jani, 2015; Esen, 2004; Sharma et al., 2005; Hussein et al., 2008; Kumar et al., 2010; Panwar et al., 2010; Harmim et al., 2012; Singh et al., 2014; Soria-Verdugo, 2015; Mahavar et al., 2017) either performs on a quality thermal heat storage (sensible and latent) or direct electrical back-up for possible cooking. Although, evening cooking (for light stuffs only) is possible on a SBC by using PCM but it is a slow process and due to absence of solar irradiance or electrical back-up it could not be a long term process. This will work until the PCM gets completely discharge (i.e, 1–2 h only). There are few articles that demonstrate thermal performance improvement by improving the design of solar cooking unit or cooking vessels (Oturani et al., 2002; Rao and Subramanyam, 2003; Nandwani, 2007; Kurt et al., 2008). But the present improved design of solar cooker is better in terms of overall year round performance and can be efficiently used at any location of the world.

The quality of cooked food has also found good. It was totally safe and healthy. Another major benefit of the present design is that it can be functioned like a microwave oven to warm the cooked food during the off sunshine hours or night. For this, the present SBC has to be performed on forced convection by closing its lid (i.e., top cover with mirror booster), than it will act like a close chamber. The enclosed hot air with a temperature around 110 °C will keep the food hot inside the SBC. It is notable that a microwave oven consume around 1–1.5 kW of electricity for the same.

Although electrical backup solar cookers are a good option but the present design meets to consumer pattern of cooking. In the present work, the duct, fan and halogen lamp plays an important role in heat transfer. Here, forced convection has been created by using a fan of 10 W. This fan has been controlled in such a way that it blows the air for a minute and then stops for next 03 minutes. This cycle is continuously repeated for the smooth conduction of all the experiments. The fan blow the air which carry heat energy of halogen lamp inside the cooking cabinet through convection (which is an efficient method of heat transfer) and light from the lamp generates the artificial flux which is an add on to the direct exposure of sun energy and this results in efficient cooking. A convection cooking unit heats the food much quicker in comparison of an ordinary electric type cooker because there is a fan that blows the hot air around and this reduce the cooking times by 20%, compared with electric cookers. So, in the present design, a better heat transfer takes place through radiation, conduction and convection which results in efficient cooking within specified time while electric type cooker deals with conduction and convection (convection is not much high) only and therefore take much time for cooking in comparison of present system.

Overall, the concept of forced convection in solar box cooker has successfully assessed. By this design one can easily minimize the time spend in cooking as well as to keep the food hot after cooking. The use of trapezoidal duct is considerable as a key component for fast thermal response of solar cooker at forced convection mode and can't be neglected. Besides this, the same unit can also be considered a small capacity multipurpose solar cooker cum air heater for winters which can cook the food as well as provide the hot air in small rooms. One can get easily the hot air to the surrounding if the lid of the cooker is partially opened.

Overall, this is the first kind of solar box type cooker which performs on forced convection and feasible to cook almost types of edibles in poor ambient conditions by consuming only 210 W. Although BIS has not specified any standard for hybrid solar cooker but yet the present system follow the standard of BIS and therefore can be considered as a standard solar cooking device. It is also notable that some of the solar box type cookers with electrical backup existing in the Indian market had been evaluated in SPRERI (Evaluation of Solar Box Cooker with Electrical Backup, 1998). They have a power rating of 250–500 W and the present system is within this specified range.

5. Conclusion

A new type of solar box cooker has been designed and fabricated.

Table 3
Estimated values of some important parameters.

Parameters	Value (W/m^2 °C)	Parameters	Value (W/m^2 °C)
h_{rlug}	7.1	h_{cealg}	14.6
h_{rvlg}	9.2	h_{cdea}	31.1
h_{rugs}	5.9	h_{cpae}	16.9
h_{rplg}	9.8	h_{cvwea}	27.3
h_{cuga}	11.7	h_{cvf}	451.3
h_{clug}	5.5	–	

Table 4
Uncertainty of some major performance parameters.

Sr. No.	Parameters	Uncertainty
1	Solar radiation	± 0.31%
2	Ambient temperature	± 0.24%
3	Wind velocity	± 2.9%
4	Thermal efficiency	± 0.96%
5	Heat transfer	± 1.9%
6	Overall heat loss	± 2.1%
7	Plate temperature	± 4.6%

Table 5
Time taken in cooking of some edibles for various loads.

Date	Substance	m (kg)	T_{amb} (°C)	Time (minutes)	Efficiency	Results
07.6.17	Pulse	0.60	39	96	37%	Good ripped (tasty)
08.6.17	Rice	0.75	38	110	43.7%	Good ripped (tasty)
09.6.17	Boneless mutton	0.50	40	13	31.9%	Hard ripped (appetizing)
10.6.17	Egg	16 eggs	39	115	41%	Boiled
11.6.17	Potato slices	1.2	37	91	45.5%	Boiled

The present system has been tested on four different configurations for its thermal performance. In first two configurations the system has been operated only on solar radiant energy. The estimated parameters for first two configurations were as; first figure of merit – 0.12 m^2 °C/W, second figure of merit – 0.41 m^2 °C/W, thermal efficiency – 38.10%, cooking power – 55.31 W, heat transfer coefficient – 34.51 W/m^2 °C and overall heat loss coefficient is 5.10 W/m^2 °C. After the testing of SBC on above configurations, the system has been modified into a hybrid SBC and tested for third and fourth configurations. Subsequently the successful testing on these two configurations, it can be concluded that this is the first kind of SBC which can perform on forced convection with the help of a specially designed duct integrated with a 200 W halogen lamp and a low power fan. The system has been found adequate for almost all types cooking substance in poor ambient conditions. The system is found better on load conditions. The estimated parameters for third and fourth configurations are as; first figure of merit – 0.12 m^2 °C/W, second figure of merit – 0.46 m^2 °C/W, thermal efficiency – 45.11%, cooking power – 60.20 W, heat transfer coefficient- 46.86 W/m^2 °C and overall heat loss coefficient is 6.01 W/m^2 °C. Results shown that the present design successfully meet to the BIS standards and can cook almost edibles in poor ambient conditions by consuming only 210 W.

Besides the cooking performance can be enhanced and cooking time can be reduced by producing more artificial flux through using a more wattage of halogen lamp (say 400 or 500 W) or by providing some quality thermal energy storage (under the hollow balls) and by increasing number of mirror boosters (the work is under study for a year round performance). The unique feature of the present solar cooking system is its robust design and fast thermal response of cooking. The present design of SBC has been found as an adequate clean cooking system for efficient cooking (without pollution), round the globe especially for developing countries and isolated areas.

Conflicts of interest

Author has no conflict of interest.

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