Solar Energy 159 (2018) 628–637

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

# Performance characteristics of a new hybrid solar cooker with air duct

Abhishek Saxena*, Nitin Agarwal

*Department of Mechanical Engineering, Moradabad Institute of Technology, Moradabad 244001, India*

A R T I C L E I N F O

*Keywords:*
Heat transfer
Heat loss
Solar box cooker
Thermal performance

A B S T R A C T

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.

* Corresponding author.
*E-mail address:* culturebeat94@yahoo.com (A. Saxena).

https://doi.org/10.1016/j.solener.2017.11.043
Received 19 August 2017; Received in revised form 12 November 2017; Accepted 18 November 2017

**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/$m^2$) |
| $\tau_g$ | glass transmissivity |
| $\alpha_g$ | absorptivity of the glass |
| $\alpha_v$ | 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*

| | |
|---|---|
| $\eta$ | 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