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Enhancing Box Type Solar Cookers by Using Jatropha Oil as Sensible Heat Storage Medium

Jacques Nébié [a*], Kayaba Haro [b], Drissa Ouédraogo [c], Koumbem W. N. Daniel [d], Boukaré Ouédraogo [e], Boubou Bagré [f], Iliyassé Konkobo [f], Armand Korsaga [f], Sidiki Zongo [f], Tizane Daho [f] and Antoine Béré [f]

[a] Université Thomas Sankara, Saaba, Burkina Faso.
[b] Institut de Recherche en Sciences Appliquées et Technologies, Ouagadougou, Burkina Faso.
[c] Université NAZI BONI, Bobo Dioulasso, Burkina Faso.
[d] Centre Universitaire de Kaya, Kaya, Burkina Faso.
[e] Université Norbert ZONGO, Koudougou, Burkina Faso.
[f] Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This research paper is based on an assessment of the performance of a box-type solar cooker insulated with kapok wool and incorporating a thermal heat storage unit. The heat storage material used in this work is Jatropha Curcas seed oil which is available locally as well as kapok wool. The

**Corresponding author: E-mail: jacquesnbi@yahoo.fr;*

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realized can offer an economically viable alternative while avoiding environmental deterioration caused by the significant use of biomass and fossil energy sources for cooking purposes. The different tests based on existing standards permitted to determine the thermal performance parameters of the cooker such as the first figure of merit (F_1) and the second figure of merit (F_2) which were determined to be F_1= 0.13 and F_2= 0.31. The cooker efficiency η = 47.07 %. The American Society of Agricultural Engineers for Solar Cooking (ASAE S580.1) is used to determine the cooking power and it is found to be P =123.2 W. In addition, a cooking test enabled to cook 0.5 kg of beans for around 3 hours.

Keywords: Solar cooker; solar energy; jatropha curcas seeds; heat storage; performance.

1. INTRODUCTION

Cooking food is an indispensable process that requires energy resources of all nature. However, in developing countries and particularly in rural areas, these sources are mainly from biomass (i.e. wood, agricultural wastes, etc.) with harmful consequences for environment and human beings (Anilkumar et al. 2021). In fact, household air pollution due to the utilization of conventional cooking fuels caused around 4 million untimely deaths in 2018 (Anilkumar et al. 2021). According to the World Energy Outlook 2020; due to pandemic in 2020, the progress in providing clean cooking fuels like LPG has declined drastically and there is still 2.6 billion people lacked clean cooking fuel (Anilkumar et al. 2021). Solar cooking can be an efficient solution to tackle this problem because solar cookers provide a sustainable source of energy that can be used for cooking purposes (Bhatt et al. 2012, Nébié et al. 2021). Thus, solar cooking system has gained more attention and has become a popular cooking system around the world (Aramesh et al. 2019, Khairnasov et al. 2016). The primary reason limiting the use of solar energy for cooking is its intermittence (Maina et al. 2019). To overcome this issue, solar cooking systems require energy storage for a proper use during periods with weak solar radiations. Several solar cooking systems with and without energy storage have been proposed (Saxena et al. 2011, Cuce 2013, Muthusivagami et al. 2010). But these works have always highlighted problems of complexity and costs (Mawire 2015). A good sensible heat storage material available locally is a viable option to enhance solar cookers performance and strengthen their autonomy (Mawire 2015).

Jatropha Curca crude oil is an inedible oil presenting interesting properties to be a good heat transfer oil and sensible heat storage material (Mishra 2021), which is available and accessible locally in Burkina Faso. Jatropha curcas is a drought-tolerant plant which fruits contain oil that can be used as fuel substitute (Toonen 2009). In this work, a solar cooker is fabricated by using optimal conception parameters determined in our previously works (Nébié et al. 2019). It is equipped with a heat storage unit using Jatropha Curcas oil as heat storage medium. The performance of the system is then evaluated using well known standards.

2. MATERIALS AND METHODS

2.1 Materials

The solar cooker developed consists of two trapezoidal boxes separated by kapok wool used as thermal insulation. The opening surface is double-glazed to minimise heat loss by convection between the inside of the cooker and the surrounding environment. The dimensions of the cooker were determined taking into account the optimal design parameters determined in our previous works (Nébié et al. 2019). Fins on the storage unit facilitate better heat transfer from the absorber to the storage material. The upper side of the storage unit is the cooker absorber. Fig. 1 shows the scheme of the device. The storage material is Jatropha oil which is an inedible oil produced by pressing the seeds of Jatropha Curcas which is available locally thanks to its virtues (Toonen 2009).

2.2 Methods

The performance of the cooker with a heat storage material integrated has been evaluated using both a no-load test and a load test. The performance parameters, first and second figure of merit were calculated.

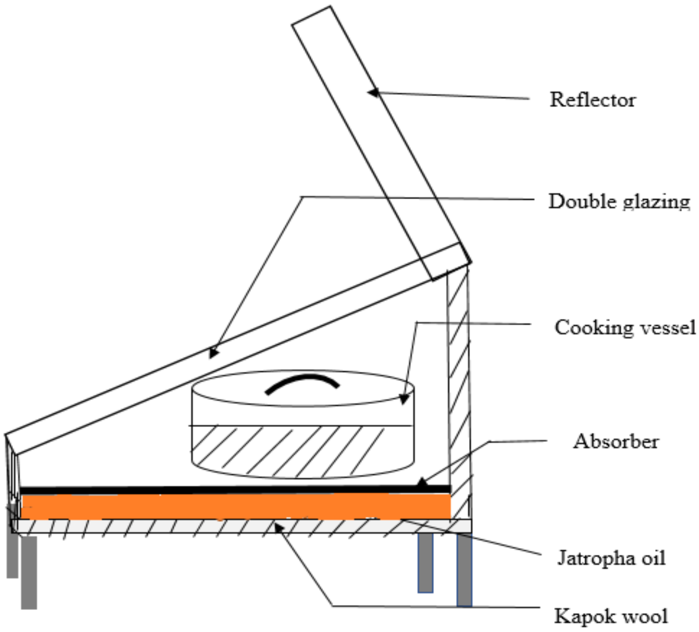

Fig. 1. Scheme of the device

- Equation 1 is used to determine the first figure of merit F_1, which is the ratio of optical efficiency to heat loss factor (Mullick et al. 1987).

$$F_1 = \frac{\eta_0}{U_L} = \frac{T_{ps} - T_{as}}{I_G} \quad (1)$$

Where η_0; U_L; F_1, T_{ps}, T_{as}, I_G are, in that order, the optical efficiency, the global heat loss coefficient, the absorber plate's stagnation temperature (°C), the ambient temperature (for stagnation), and the sun global irradiation (W/m²).

- The Second figure of merit F_2 allowing the assessment of heat transfer between the vessel and its content equation is given by Equation 2 (Mullick et al. 1987, Mullick et al. 1997).

$$F_2 = F'\eta_0 C_R = \frac{F_1 (mc)_W}{A_C t} \ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w_i} - \overline{T_a}}{\overline{I_G}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w_f} - \overline{T_a}}{\overline{I_G}}\right)}\right] \quad (2)$$

where F', C_R, c_w, m_w, T_{w_i}, T_{w_f}, $\overline{T_a}$, $\overline{I_G}$ are heat exchange factor, ratio of thermal capacities, water specific heat, mass of water, water initial and final temperature, the ambient average temperature and the average solar global radiation.

To evaluate the performance, the cooking power P is also considered. Funk showed that this figure is among the finest at illustrating the thermal performance for various cooker sizes and rates of heat gain (Funk 2000). It is calculated using equation 3 (American Society of Agricultural Engineers 2003):

$$P = \frac{m_w c_w (T_{w_f} - T_{w_i})}{\Delta t} = \frac{m_w c_w (T_{w_f} - T_{w_i})}{600} \quad (3)$$

- The cooker thermal efficiency (η)is given by equation 4 (Saxena et al. 2011):

$$\eta = \frac{m_w c_w \left(T_{wf} - T_{wi}\right)}{A_c I_G \Delta t} \quad (4)$$

3. RESULTS AND DISCUSSION

The stagnation test results are shown in Fig. 2, together with the changes in the storage oil temperature, absorber temperature, ambient temperature, and solar global radiation. Between 9:04 a.m. and 3:24 p.m., the absorber's temperature ranges from 77 °C to 158.3 °C, while the storage temperature ranges from 61.6 °C to 150 °C. At 12:34 p.m., the maximum solar radiation value of 923.95 W/m² is obtained, while the maximum storage temperature is reached at 1:54 p.m. This test enabled the determination of the first figure of merit. According to Bureau of Indian Standards 2000, parameters used for the calculation of F_1 are: T_{ps}=158.3 °C; T_{as}=48.4 °C et I_G=830 W/m². Thus, first figure of merit is calculated to be F_1=0.13, which shows that the cooker constructed is a higher grade solar cookers according to the Bureau of Indian Standard (Bureau of Indian Standards 2000).

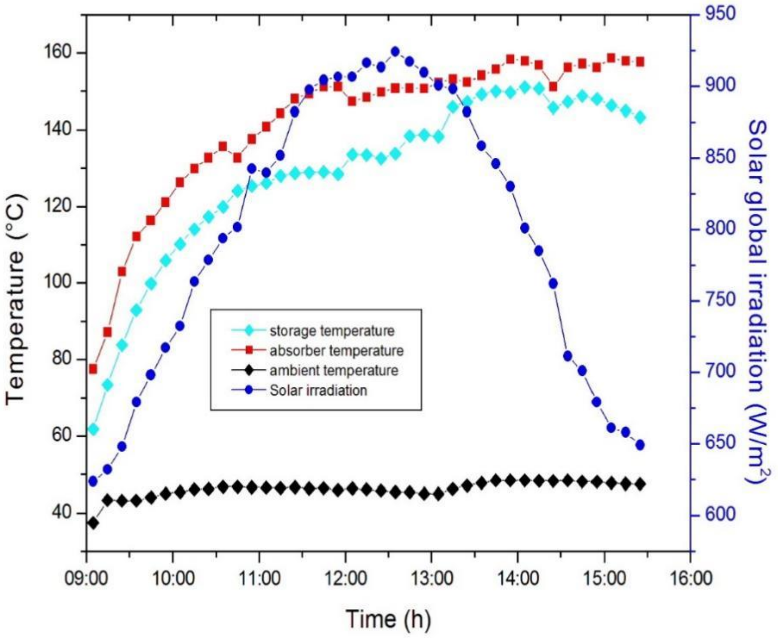

Fig. 2. No-load test

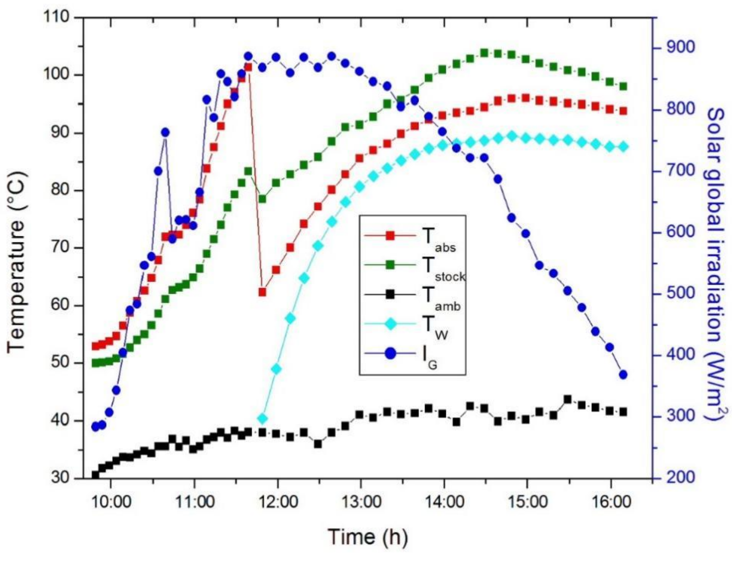

Fig. 3. Water heating test

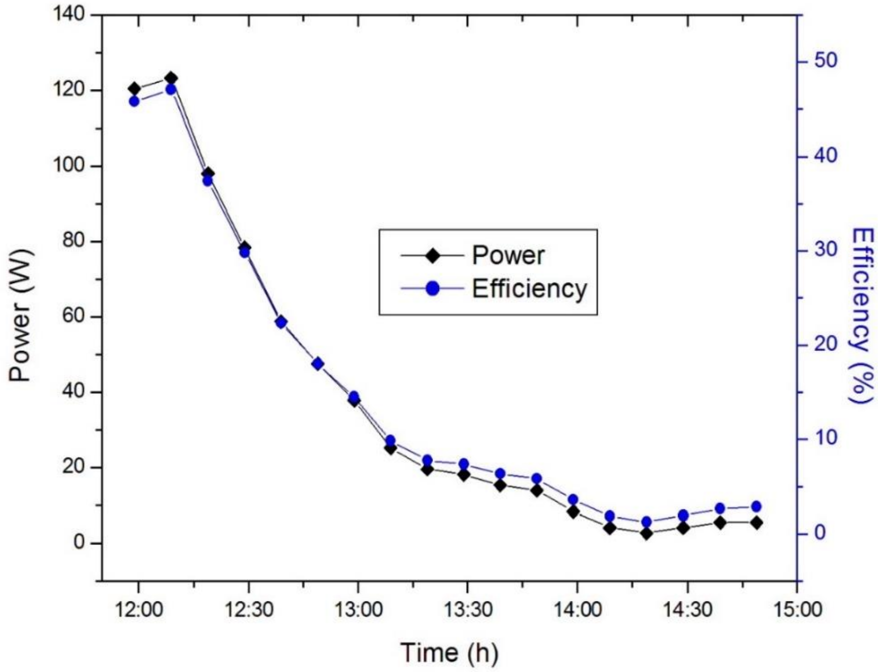

Fig. 4. Instantaneous power and efficiency

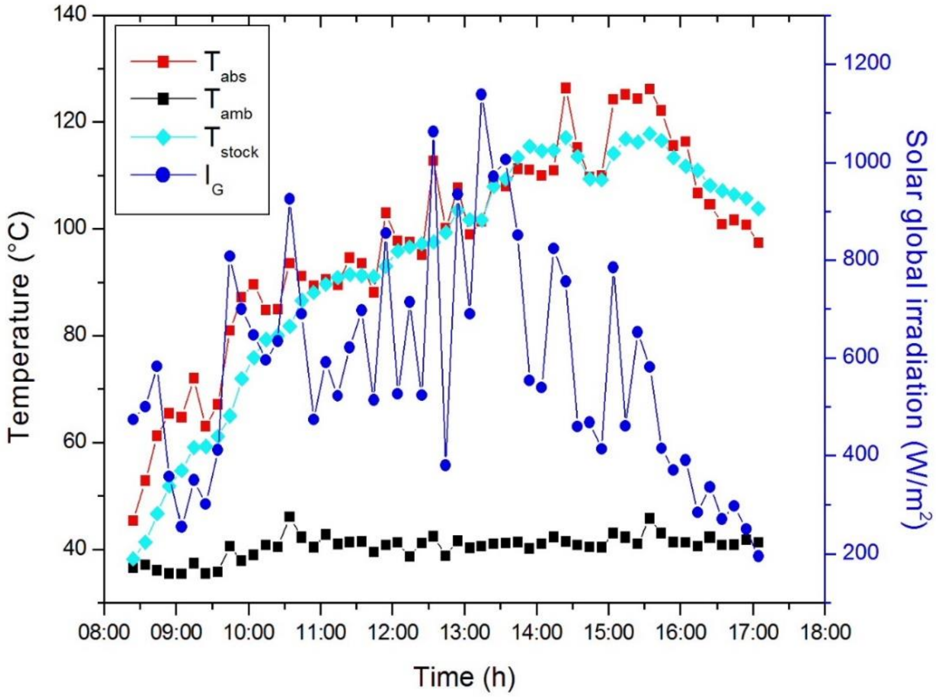

Fig. 5. Operation of the cooker in cloudy weather

Fig. 3 shows the results of water heating test. This experiment is marked by cloudy disturbance at the beginning of the day. After the cooker is exposed to the sun until the absorber reaches a temperature of 101.3 °C and a maximum solar radiation of 886.65 W.m^{-2}, the load is introduced at 11:38 a.m. While, the storage oil temperature varies between 50 et 103.8°C during the experience. A sudden drop in absorber temperature is observed due to the high convective and radiative heat losses caused by the cooker opening during the loading process. This sudden drop is also observed with the storage oil, showing a transfer of thermal energy from the storage oil to the absorber. The second figure of merit obtained is F_2=0.31 by using equation 2, that indicates a good heat exchange in the solar cooker (Mullick et al. 1997, Saxena et al. 2011).

These values of F_1=0.13 et F_2=0.31 indicates good insulation and efficient thermal exchange inside the cooker thanks to the increasing of the cooker thermal inertia due to the storage system (Lokeswaran 2012). This outcome demonstrates that cooking a variety of dishes in a reasonable amount of time is possible with the proposed box-type solar cooker that integrates sensible heat storage material (El-Sebaii et al. 1994, Mawire et al. 2014). Ephrem Milikias et al. 2021, studied recently different solar cookers using heat storage materials and obtained F_1= 0.1349 for improved solar cooker with black stone as a thermal energy storage, F_1=0.1238 for improved solar cooker with concrete as a thermal energy storage.

Fig. 4 shows the temporal variation of the cooker power and thermal efficiency. The highest power and efficiency are 47.07 % and 123.2 W respectively.

According to Öztürk 2004, the efficiency of the box-type solar cookers without storage material varies between 3.05 % and 35.2 %. In addition, an experimental study conducted with this same cooker without storage gave a maximum power of 87.5 W with a maximum efficiency of 35.45 % (Nébié et al. 2021). This interesting result is due to the sensible heat storage as a back-up heat source and proves the contribution of that heat source to the enhancement of the box type solar cooker performances.

Testing during cloudy weather: Fig. 5 shows the thermal behaviour of the cooker integrating a heat storage unit during a cloudy weather condition. Fluctuations in the solar radiation curve indicate a cloudy period. The low intensity of solar radiation due to clouds poses a significant obstacle to the proper operation of solar cookers (Amusan et al. 2019). Despite this permanent cloud disturbance, the temperature of the absorber is almost stable. Moreover, this temperature reaches 103 °C at 11:54 p.m. and the stagnation temperature of 126.4 °C at 2:24 p.m. The achievement of these performances demonstrates that the cooker is really capable of cooking, although under poor weather conditions (Aremu et al. 2013). This proves that heat storage in solar cooker contributes to the cooker's energy independence and autonomy which is its main attraction (Khairnasov et al. 2016).

Cooking test: Fig. 6 shows the evolution of temperatures during the cooking of 0.5 kg of beans.

The cooker is exposed to the sun at 9 am, so that the absorber temperature reaches 100 °C by 10 am. It is then opened for the introduction of the beans to cook. When the cooker is opened, the temperature of the absorber drops significantly, falling below the storage temperature, which continues to charge as shown by its growing temperature.

After 2 h 55 min of operation (i.e. at 12:55 p.m.), the cooker is opened to check the cooking of the bean. The figure shows that this causes a drop in the temperature of both the absorber and the air. A considerable drop in the temperature of the heat storage material is also noted. This demonstrates that thermal energy is moved from the storage material to the absorber to compensate the heat losses caused by the opening of the cooker.

The check-up indicates that, the beans were almost cooked at a temperature of 92.6 °C.

After closing the cooker, the temperature of the bean quickly rises to the temperature just before opening in 25 minutes, while solar radiation decreases. These results obtained show the advantage of storage for this solar cooker. In particular, in mitigating the effects of disturbances (clouds, opening of pots for stirring or introducing spices) during the cooking process.

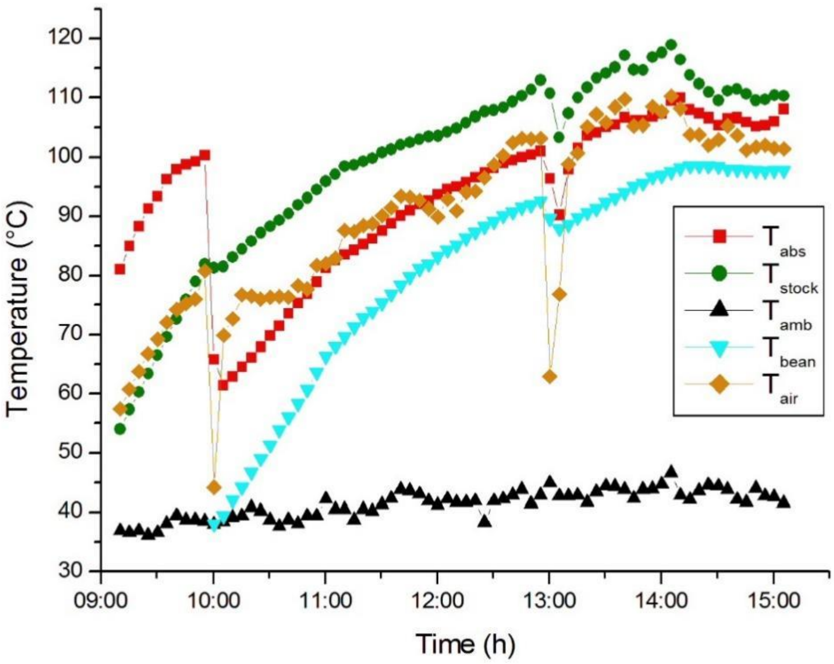

Fig. 6. Cooking test

4. CONCLUSION

A box type solar cooker integrating heat storage system with Jatropha Curcas seeds raw oil as heat storage material was studied. The assessment of performance parameters according to international standards clearly showed the improvement of locally made box type solar cooker. In fact, the results showed that it is a cooker of grade A with cooking power P=123.2 W and thermal efficiency η = 47.07 %. The cooking test and test during cloudy weather showed the ability of the cooker integrating heat storage to attenuate the solar energy intermittence effects on the solar cooker operation. From this result, it can be concluded easily that the use of sensible heat storage can remove limits of using solar cookers due to solar energy intermittence. However, the introduction of a storage system to solar cookers could increase their cost. Hence the need to look for locally available heat storage materials. Although the cooker developed in this work presents interesting performances, future work on life cycle cost analysis is necessary.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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