Thermal performance of a solar box cooker with forced convection heating and sensible heat storage

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Abstract

A solar box cooker using a 12 V DC fan in the forced convection mode is experimentally evaluated. The experimental tests use two black stainless steel cooking pots with and without storage. The storage system consists of a glass bowl with 500 g of granite, and one pot is placed inside the glass bowl. The experimental tests are carried out for a 10-hour interval. The first part of the experiments involves testing without any load for 4 hrs to establish the stagnation temperatures. The second part of the experiment consists of loading the cooking pots with 1 litre of water for 6 hrs. The pots with and without storage are tested simultaneously in the solar cooker. Experimental results without the fan blowing and without the load show that the highest temperatures for the storage and non-storage cases are around 142 and 123 ºC, respectively. For the case of forced convection using the fan without the load, the corresponding maximum temperatures in the cooking pots are around 156 and 135 ºC, respectively. During the 6 hrs water heating cycle, maximum temperatures attained for the storage and non-storage cases are 92 and 81 ºC without the fan. These maximum temperatures are comparable to the forced convection maximum temperatures of 93 and 82 ºC, achieved at about the same time. The first figure of merits (F_1) for the storage case with and without the fan of 0.121 and 0.110 ºC/(W/m^2) is greater than those of the non-storage case of 0.102 and 0.092 ºC/(W/m^2), respectively. Using the fan results in an improvement of the first figure of merit. The storage case shows better performance in terms of the higher cooking temperatures achieved and the higher first figure of merits; however, there is no advantage to using forced convection when the pots are loaded after achieving higher temperatures in the no-load tests.

Keywords: Forced convection, Sensible heat storage, Solar box cooker, Thermal performance

1. Introduction

Solar cookers are environmentally friendly cooking devices that use the sun's energy, thus reducing greenhouse gas emissions [1]. The three main types of solar cookers are concentrating solar cookers, panel cookers, and box cookers. Box and panel cookers achieve lower operating temperatures than concentrating solar cookers, but they are safer and do not need too much operator intervention, like consistently tracking the sun and ensuring that food is not burnt [2]. Panel cookers are usually limited to smaller cooking pots and have lower efficiencies than box solar cookers. In terms of the compromise between safety, reasonable cooking size, cost, ease of use, and acceptable cooking temperatures, the box solar cooker is a viable option compared to the other options.

As with all solar cookers, box cookers cannot operate optimally under low solar radiation conditions, and their cooking speed and temperatures are low. Recent work has focused on incorporating thermal energy storage (TES) with solar box cookers to improve their off-sunshine performance [3-8]. Goyal and Eswaramoorthy [3] presented theoretical and experimental results of a solar box cooker with sensible heat storage. Their results showed that using marble as the storage material made cooking possible at night. Verma et al. [4] developed an analytical model for a solar box cooker with sensible heat storage. The results revealed that the storage should be charged for the whole solar period but for an optimal period, which is valuable for storing thermal energy. Cuce [5] presented an experimental investigation of a box solar cooker using Bayburt stone as the TES material. Bayburt stone was suitable for s efficient and continuous solar cooking. Cooking A multi-criteria decision-making technique for an optimal section of phase change materials (PCMs) for a solar box cooker was presented by Anilkumar et al. [6]. Erythritol was recommended as the most suitable PCM for a solar box cooker with storage. Coccia et al. [7] also investigated the use of erythritol in a solar box cooker. They found

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that erythritol extended the average load cooling time, in the range of 125–100 °C, to around 351 % compared to the case without storage. Although latent heat storage using PCM provides a more significant energy storage density than sensible heat storage, its main drawbacks are the cost, low thermal conductivity and degradation after numerous charging and discharging cycles. Thus, sensible heat storage is more viable in terms of cost. A viable sensible heat TES material is granite, used in recent solar thermal applications because of its cheapness, non-toxic nature, and availability worldwide [8-12].

A method to improve heat transfer and operating temperatures in a solar box cooker uses a heat circulation fan, which has yet to be explored [13]. To improve the thermal performance of solar box cookers, a forced convection solar cooking mode using a 12 V DC fan powered by a battery charged with a 30 W solar panel is presented. This paper considers two black stainless cooking pots with and without heat storage. The heat storage material used is granular pebbles. The paper aims to investigate the effect of forced convection on the solar cooking process for cooking pots with and without storage. The novel aspect of the study is comparing solar cooking pots with and without storage in a forced convection mode, which has rarely been reported. The storage material is also enclosed in a glass bowl to reduce heat losses, and this has yet to be investigated.

2. Experimental method

The experimental setup showing two cooking pots inside a solar box cooker is shown in Figure 1. All pots are made of stainless steel, and they are painted black. One pot is enclosed in a glass bowl containing 500 g of granite as the sensible heat storage material. The capacity of the pots is 1 litre. The dimensions and specifications of the solar box cooker, cooking pots, glass bowl and storage material are shown in Table 1. A 12 V DC fan is driven by a 12 V 7 Ah battery that is charged by a 30 W solar panel (not shown in Figure 1). The battery is charged with a maximum power point tracking (MPPT) charge controller. The fan runs continuously for 10 hrs during the experimental test period when testing forced convection heating. The first four (4) hours of the experimental tests involve heating the pots without the load to establish the stagnation temperatures. After that, the next six (6) hours are water heating tests with one litre of water placed in each pot. Experimental tests are conducted with and without the fan to compare natural and forced convection heating. Two K-type thermocouples measure the temperatures in the pots during the experimental tests. Another K-type thermocouple measures the ambient temperature. Global solar radiation is measured using a Kipp and Zonen CMP11 pyranometer. All thermocouples and the pyranometer outputs are connected to the channels of a Sefram DAS 240 datalogger, which records the experimental data at 10 s intervals.

Table 1: Dimensions and specifications of the solar box cooker and associated experimental components

Parameter	Value
Length of box cooker (m)	0.590
Width of box cooker (m)	0.540
Height of box cooker (m)	0.250
Area of glass glazing (m^2)	0.207
Aluminium reflector area (m^2)	0.230
Diameter of cooking pot (m)	0.130
Height of the pot (m)	0.100
Volume of the pot (m^3)	0.001
Material of pot	Stainless steel
Volume of glass bowl (m^3)	0.025
Storage material	Granite
Storage mass (kg)	0.500
Specific heat capacity of granite (J/kgK) [9]	798

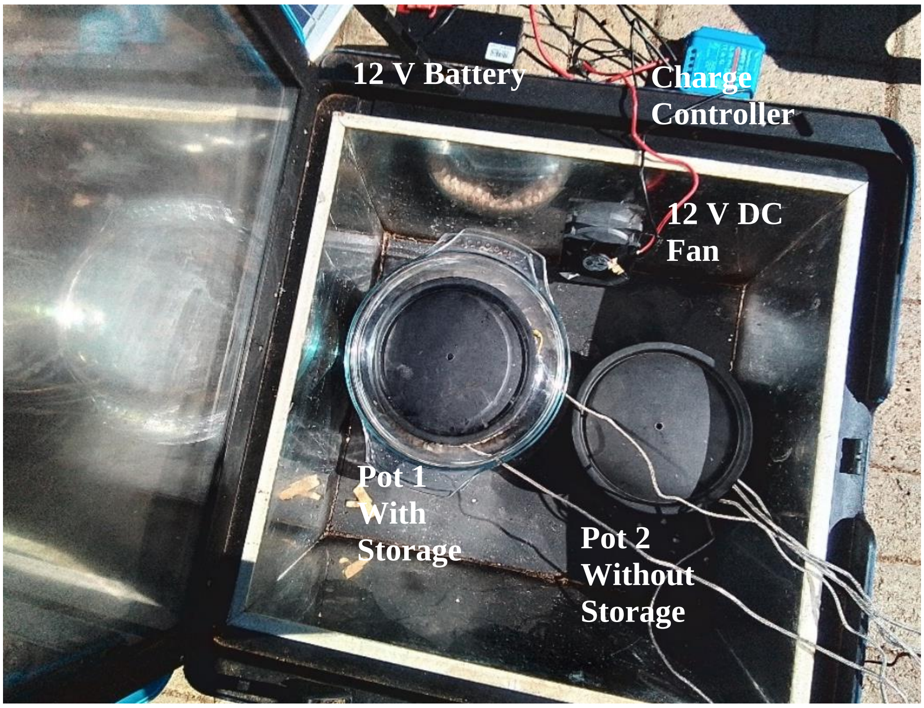

Figure 1: Experimental setup of the solar cooking experiments showing the storage and non-storage cooking pots, the 12 V DC fan, the charge controller, and the 12 V battery.

3. Thermal analysis

To evaluate the solar box cookers with and without storage around the cooking pot, the first figure of merit (F_1) proposed by Mullick et al. [14] and also used in Refs. [3, 12] is utilized. It is defined as:

$$F_1 = \frac{T_{abs} - T_{amb}}{I} \tag{1}$$

, where T_{abs} is the stagnation temperature of the absorber (empty pot in this case), T_{amb} is the ambient temperature and I is the solar radiation. Average values towards the end of the heating tests were considered in the experiments. Other important quantities, such as the thermal efficiency and the second figure of merit (F_2), were not considered as the load was only added after peaking solar radiation conditions had elapsed. These parameters are usually evaluated under load conditions at intervals of ±2 hrs from solar noon. It was not possible to calculate the second figure of merit and the water heating (thermal) efficiency using an empty pot during stagnation temperature heating tests. These parameters will be presented in future work since the aim of the study was limited to understanding the effect of forced convection on the temperatures of a solar box cooker with and without heat storage surrounding the cooking pot.

Another important parameter that could be derived from the experiments was the cooking power after loading the pots with water. It is expressed as [3]:

$$P_W = \frac{m_w \left(T_{Wf} - T_{Wi}\right)}{\Delta t} \tag{2}$$

, where m_w is the mass of the heated water, T_{Wf} is the final maximum water temperature achieved, T_{Wi} is the ininitial water temperature and Δt is the time interval to from the initial to the maximum water temperatures.

4. Results and discussion

Figure 2 (A, B) shows experimental solar heating tests with and without using the fan for a 10-hour test period on 9 March 2024 (without fan) and on 10 March 2024 (with fan). The average solar radiation for the test using the fan (740 W/m^2) is comparable to that without using the fan (772 W/m^2). The maximum temperature achieved for the natural heating test using the pot with storage is around 142 ºC compared to 123 ºC for the pot without storage. This suggests that the glass bowl with storage reduces heat losses compared to the pot without storage. Higher temperatures are achieved for the forced convection case using the fan during the first four hours of heating compared to the case without the fan. The maximum temperatures achieved by the storage and non-storage pots are around 156 and 135 ºC, respectively. These results suggest that forced convection in the solar box improves the heat transfer rate, resulting in higher temperatures. During the 6 hrs water heating cycle, maximum temperatures attained for the storage and non-storage cases are 92 and 81 ºC without the fan. These maximum temperatures are comparable to the forced convection maximum temperatures of 93 and 82 ºC, achieved at about the same time. The results suggest that forced convection is insignificant when the pot is fully loaded to its maximum capacity.

Additionally, the pots without forced circulation show slightly higher temperatures at the end of the testing period. This suggests the fan tends to cool the surrounding air when solar radiation values become low. The temperature difference between the storage and non-storage case is more significant during forced convection heating, suggesting that this mode of operation is more beneficial to the case with storage since it is circulated more in the storage medium.

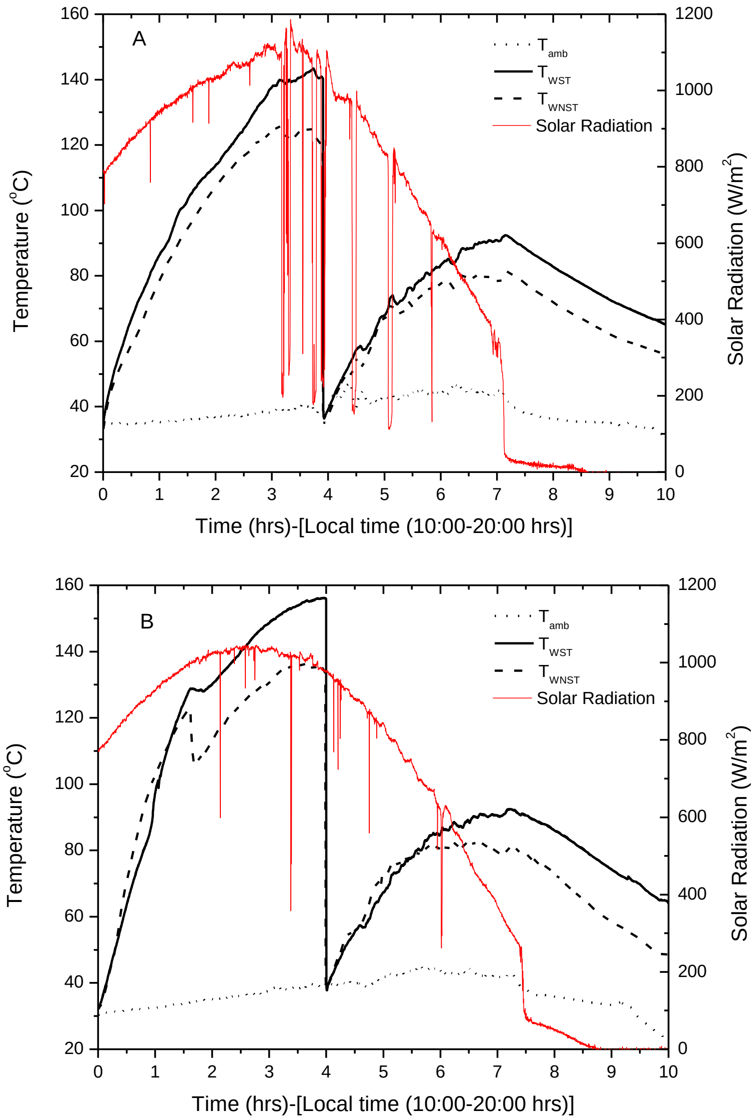

Figure 2: Experimental results of solar heating tests (A) without forced convection (no fan) and (B) using the fan (forced convection).

The first figures of merit obtained for the storage case with and without the fan are 0.121 and 0.110 $^oC/(Wm^2)$, respectively, showing better performance for forced convection. Similarly, the forced convection mode for the non-storage case shows a higher first figure of merit of 0.102 $^oC/(W/m^2)$ compared to 0.092 $^oC/(W/m^2)$ for the case without a fan. The storage case with a glass bowl reduces heat losses, showing higher first-of-merit values compared to the non-storage case. The values of the first merit obtained in the experiments are higher or comparable to related recent work on solar box cookers with sensible heat storage [3, 12] F_1 values obtained by Saxena et al. [12] in the range of 0.011-0.012 $^oC/(W/m^2)$ are much lower than those presented in this paper of 0.092-0.121 $^oC/(W/m^2)$. On the otherhand the F_1 value of 0.1325 $^oC/(W/m^2)$ obtained by Goyal and Eswaramoorthy [3] is slightly greater but comparable to the maxmimum F_1 value of 0.121 $^oC/(W/m^2)$ obtained in this work. The water heating powers for the cases without the fan are 19.0 and 16. 6 W, respectively, for the non-storage and storage cases. These water heating powers are comparable to the cases with fan of 20.5 and 16.0 W, respectively. A direct comparision of the water heating power values with work presented in Refs. [3, 12[is not possible since the authors calculated the water heating power during the solar heating period unlike our case where we first achieved maximum stagnation temperatures and then added water. Although the forced convention mode shows higher temperatures and the first figures of merits compared to the mode without the fan during no-load conditions, there is no advantage of using forced convection when the pots are loaded after achieving higher temperatures in the no-load tests. This is because similar temperatures are obtained after loading the pots with water, regardless of the higher no-load temperatures obtained with forced convection. These similar temperatures resulted in almost similar water heating powers.

5. Conclusion

Experimental results of solar heating tests with and without forced convection have been presented for storage and non-storage cases for a solar box cooker. The main conclusions of the experimental tests were:

1. Experimental results without the fan blowing and without the load showed that the highest temperatures achieved for the storage and non-storage cases are around 142 and 123 ^oC; the case of forced convection without the load showed higher temperatures of 156 and 135 ^oC, respectively. Higher temperatures were achieved with the storage case.
2. For the case of water heating after the no-load heating, the maximum temperatures attained for the storage and non-storage cases using the fan were 93 and 82 ^oC. These maximum temperatures were comparable to the water heating tests without the fan, where the storage and non-storage cases achieved maximum temperatures of 93 and 82 ^oC, respectively.
3. The first figure of merits (F_1) for the storage case with and without the fan of 0.121 and 0.110 $^oC/(W/m^2)$ were greater than those of the non-storage case of 0.102 and 0.092 $^oC/(W/m^2)$, respectively. The first figure of merit improved with storage and an air-circulating fan.
4. The water heating powers for the cases without the fan were 19.0 and 16. 6 W, respectively, for the non-storage and storage cases. These water heating powers were comparable to the cases with fans of 20.5 and 16.0 W, respectively.
5. Although the cases with the fan showed higher no-load temperatures and higher first-figure merits, there was no advantage of using the fan during water heating tests after stagnation temperature tests since almost similar maximum water temperatures were obtained. These similar temperatures resulted in almost similar water heating powers.

6. References

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