Original Research Article

Thermal performance assessment of a box-type solar cooker with an inclined collecting surface and kapok wool insulation

ABSTRACT

The present work reports the thermal performance of a box-type solar cooker insulated with kapok wool, a local plant with a low thermal conductivity. The experimental results obtained indicate that the absorber plate reached a maximum temperature of 155.2 °C. Moreover, the maximum power of the cooker was 87.5 W with an efficiency of 35.45 %. The first and second figure of merit parameters performed are 0.15 and 0.298 respectively. The cooking test carried out on eggs and rice was conclusive. And it appears that this solar cooker can cook an average of 464 meals per year thanks to the solar energy available in Burkina Faso corresponding to a reduction of 67.62 % in household fuel wood consumption.

Keywords: Solar cookers, Fuel wood, Performance, Solar energy

1. INTRODUCTION

Fuel wood represents nearly 81 % of energy consumption in Sub-Saharan Africa [1]. However, this significant consumption of solid biomass presents more disadvantages on the population and its environment. in fact, biomass combustion is often source of diseases which causes nearly 3.5 million deaths worldwide through the produced smoke [2]. In 2010, Africa accounts around 34 % of the global greenhouse gas emissions from wood-fuel consumption [3]. The access to modern cooking energies such as liquefied petroleum gas (LPG) is limited in urban areas and almost non-existent in rural areas of Sub-Saharan countries and particularly in Burkina Faso [4]. To reduce the consumption of wood fuels and also to guarantee affordable and sufficient cooking energy for a continuously growing population, many solar technologies have been developed among which the solar cooking systems that have extensively been developed as an alternative to the traditional biomass energy consumption as reported in [5] and [6]. The main types of solar cookers designed are parabolic, box type and panel solar cookers. The parabolic solar cookers are more suitable for all types of cooking because of the higher temperatures they can reach. However, they are limited in their use due to the risks of glare, food burning and also the high technology required and constant monitoring process [7,8]. Therefore, box type solar cookers are revealed to the widely used due to their simplicity [9,10]. According to carmody and sarkar [11], solar box cookers are well capable of supplying energy demand in African rural and poor urban household sectors. Thus, several works have been carried out on the development of high-performance box-type solar cookers for the two last decades. These studies focused on many aspects including, the impact of the orientation of a box-type solar cooker on its thermal performance, the number of reflectors used, the configuration of the absorber, the insulation and the geometry [12]–[16]. Additionally, works have been done on solar box-type cooker with a concentrator underneath that concentrates the solar radiation downwards [17]. Data on the performance of box-type solar cookers in Sub-Saharan countries is almost non-existent. However, J. Nébié et al.[18], simulated the operating parameters of a box-type solar cooker under the meteorological conditions of Burkina Faso for the realization of optimized solar cookers based on local and accessible materials. The present work aims to determine the performance of a box type solar cooker with inclined collecting surface insulated with kapok wool.

2. MATERIAL AND METHODS

2.1. Solar box cooker and measuring equipment

The box type cooker was designed according to the model described by J. Nébié et al.,[18] in their work. The important parts of the built solar box type are two plywood boxes (outer and inner box) with double glazing panes spaced by 1.3 cm of air gap. The box was insulated with kapok wool and an air gap at the bottom of the cooker between the absorber plate and the inner box. Kapok wool is a vegetable insulator available locally with interesting properties (Conductivity varying between 0.03 and 0.06 W/m.K) [19– 21]. The thickness of insulation at the bottom of the cooker is 6 cm and the angle of inclination of the opening surface with respect to the horizontal is 13° as shown in figure 1 and 2 of the built solar cooker. It consists of two plywood boxes, separated by a layer of kapok wool for insulation. The detailed parameters of the design solar cooker for the present studies are presented in Table 1.The thermal performance of the cooker was evaluated through a “no-load” and “with load” tests. The data acquisition was carried out using a midi LOGGER GL240, J thermocouples and Steca TA ES1 solarimeter.

Fig. 1. Picture of the fabricated solar box cooker

Component	Dimension	Material
Inner box	600 mm x 500 mm x 130mm x 268.5mm	Plywood
Outer box	660mm x 560 mm x 190mm x 328.5 mm	Plywood
Double glazing	615.8 mm x 500 mm	4 mm thick glass
Reflector		S-Reflect
Absorber plate	600 mm x 500 mm	Black coated aluminum
Cooking pots	Diameter: 200 mm Height: 100 mm	Aluminum

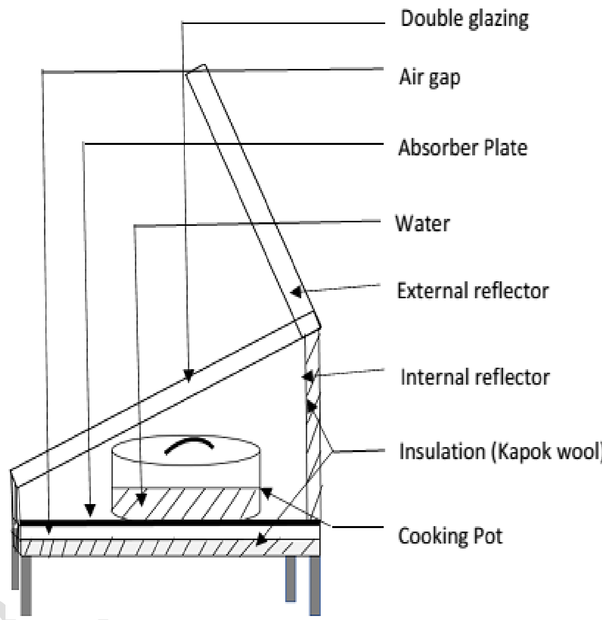

Fig.2. Scheme of the device

Table 1. Design parameters of the cookers

2.2. Thermal performances assessment

Several methods have been reported in the literature [22] for evaluating the performance of solar cookers. The most widely used are the Indian standard and the American Society of Agricultural Engineers (ASAE) standard.

2.2.1. <u>First figure of merit F_1</u>

The first figure of merit is defined as the ratio of optical efficiency to heat loss factor in the thermal performance. Experimentally, the box type solar cooker without vessels is exposed to sunshine (clear day) from the morning to the afternoon. The parameters such as ambient temperature, the absorber temperature and the global solar irradiation were evaluated at regular interval time. The governing equation of the first figure of merit evaluation is given by equation (1) [23]:

$$F_1 = \frac{T_{ps} - T_{as}}{I_G} \tag{1}$$

where T_{ps}, T_{as}, I_G are stagnation temperature of the absorber plate (°C), ambient temperature (for stagnation) and solar global irradiation (W/m²), respectively.

2.2.2. <u>Second figure of merit F_2</u>

The quantification of good thermal performance requires good heat transfer to the vessel content and low heat capacity of the cooker interior. Thus, the box cooker system should include a 'full load' (vessel with content) and kept under solar irradiation. The heat transfer between the vessel and its content defining the heat exchange efficiency factor is therefore indirectly evaluated through a new factor; the second figure of merit F_2 given by equation (2) [23, 24].

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

The sensible heating time t_s as an important parameter of the solar cooker performance determination is evaluated using equation (3) [23].

$$t = \frac{F_1 (mc)_w}{A_C F_2} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w_i} - \overline{T_a}}{\overline{I_G}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w_f} - \overline{T_a}}{\overline{I_G}}\right)} \right] \tag{3}$$

where F', C_R, c, m, T_{w_i}, T_{w_f}, $\overline{T}_a$, $\overline{I}_G$ are heat exchange factor , ratio of thermal capacities, specific heat, mass of water, water initial and final temperature, the average ambient temperature and the average solar irradiation.

2.2.3. <u>Cooking power and energy efficiency</u>

The main characteristic proposed by the ASAE S580 in a cooking process is the cooking power (P) as a good parameter in a solar cooker heating assessement [25]. Taking measurement intervals time of 10 min as proposed by P. A. Funk, the power is calculated from equation 4 [26].

$$P = \frac{(mc)_w (T_{w_f} - T_{w_i})}{\Delta t} = \frac{(mc)_w (T_{w_f} - T_{w_i})}{600} \tag{4}$$

The cooking power is corrected using a standardized insolation of 700 W/m² for a comparison of results obtained from different point's measurement at different times and comparison of different solar cookers. The normalized cooking power is therefore given by equation (5):

$$P_s = P.\frac{700}{\overline{I_G}} \tag{5}$$

The energy effiency of the solar cooker is calculated according to equation (6) [6].

$$\eta = \frac{(mc)_W (T_{W_f} - T_{W_i})}{A_C I_G \Delta t} \tag{6}$$

3. RESULTS AND DISCUSSION

3.1. Stagnation test (no-load test)

The data of the temperature and the global irradiation measurement are plotted and presented in figure 3. From this figure, it can be observed that the temperature of the absorber increases from 47.3 °C to 102.8 °C while running the test from 8:54 to 9:34. Above 9:34, this temperature increases until reaching a maximum stagnation value of 155.2 °C at 13:54 under ambient temperature of 35.8 °C with a global solar irradiation of 789.95 W/m². The temperature remains above 100 °C until after 17:00. This result is assigned to an appropriate collection surface inclination angle and internal reflectors for a maximum irradiation collection through the absorber. From the literature, the maximum temperature reached with a conventional box solar cooker was about 150 °C [27] while our box cooker model achieved a maximum temperature of 155.5 ^{o}C. The calculation of the first figure of merit (F_1) using equation 1 gives 0.15 $K.m^2.W^{-1}$. This value which ranges between 0.12 and 0.16 $K.m^2.W^{-1}$ indicates that the designed box cooker has a good optical efficiency and therefore is suitable for sufficient food cooking [6].

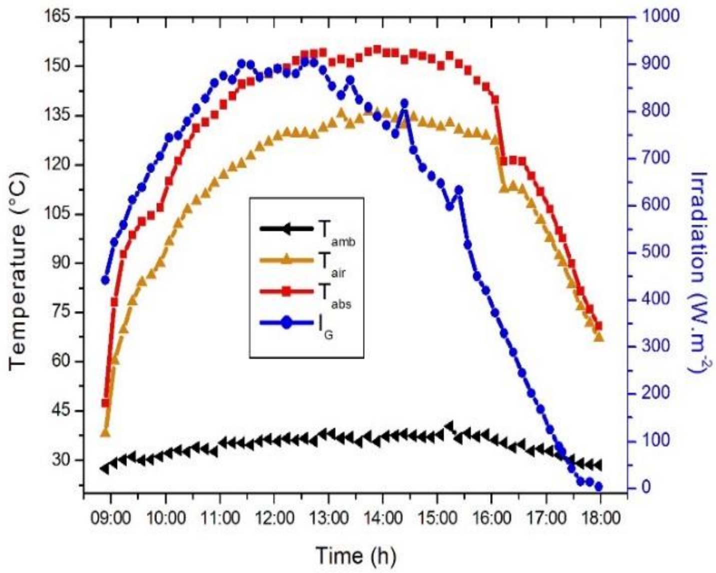

Fig.3. Time evolution of the absorber temperature (T_{abs}), the ambient temperature (T_{amb}), the internal air temperature (T_{air}) of the cooker and the global solar irradiation (I_G).

3.2. Test with load

A quantity of 2.4 kg of water was loaded and distributed between the two aluminum pans and arranged in the solar cooker. After an exposure to sun radiation for 2 hours 40 min (from 9:18 to 11:58 am), the temperature of water reached 84 °C witch is sufficient for cooking [23]. A maximum temperature of 100.4 °C is reached at 13:28 and then remained almost constant for more than 3 hours as shown in figure 4. As reported in [28], most of food cooked in the world has a high-water content and the cooking temperature required ranges from 90 to 100 °C [28]. From our test results, it can clearly be seen that, our box cooker model could be suitable for cooking and therefore it can be drawn that the designed solar cooker may be suitable for food cooking in many places around the world and particularly, in sub-Saharan countries such as Burkina Faso.

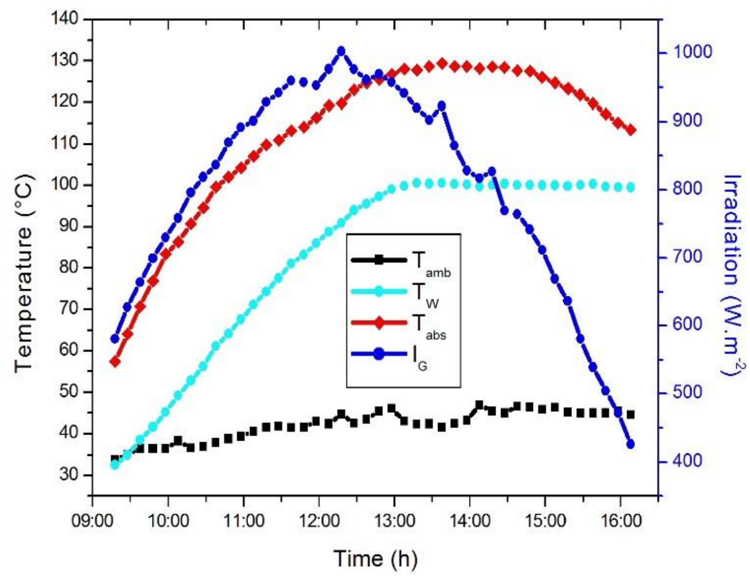

Figure 4. Time evolution of the absorber, water (T_w) and ambient temperatures and global solar irradiation.

To confirm this performance, the second figure of merit was evaluated using equation 2 and found to be F_2= 0.298. This value, which ranges between 0.254 and 0.490, indicates that the cooker model has a high heat exchange factor that leading to a significant heat transfer [6,24].

The sensitive heating time evaluated from equation 3 gives 7727.5 seconds i.e. 2 hours and 08 minutes while the time required for 2.4 kg of water heating from ambient temperature to boiling temperature is 3 h 13 min. In general, the sensitive heating time required for a conventional box type ranges from 1.727 h to 3.332 h [29] . The value of the boiling time obtained in this work is relatively better compared to those of Guidara and al. [30] and Jubran and al. [31].

3.3. Cooking power and efficiency

Figure 5 illustrates the fluctuation of the cooking power and its hourly efficiency. It can be observed that the maximum power achieved is 87.5 W and the maximum efficiency is 35.45%. These results are comparable to those obtained by öztürk [32], who carried out a comparative study between the performance of a box-type solar cooker and that of a cylindrical-parabolic cooker. He has showed that the efficiency of the box-type solar cooker varies between 3.05% and 35.2%, while the efficiency of the parabolic dish varies from 2.79 to 15.65%. Aremu and *al.*[33], obtained efficiencies ranging from 28.03 to 37% for different insulation materials such as corn bales, corn cobs, coconut fiber, polyurethane and air.

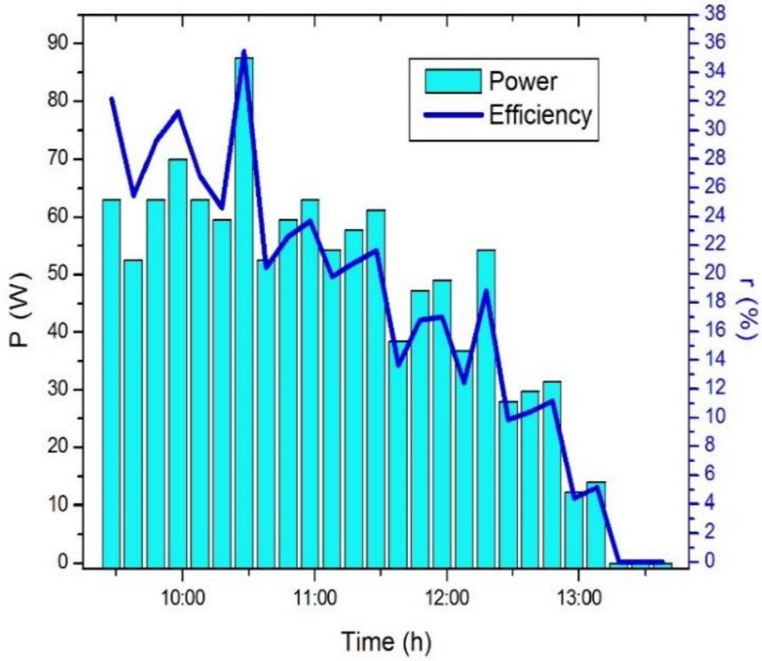

Figure 5. Instantaneous power and efficiency

In order to determine the relationship between the temperature difference and the normalized cooking power, the linear regression was used as showed in figure 6. It can be observed that the standardized cooking power decreases with temperature difference and for T_d=50°C,

$$\mathbf{P_S(T_d = 50\ °C) = 26.33\ W}$$

The slope of the linear regression line $a = 0.92$ indicates that the overall heat loss coefficient of the solar cooker is U_L=3.06 W/m².K. These values are attractive when comparing with others results in the literature [34].

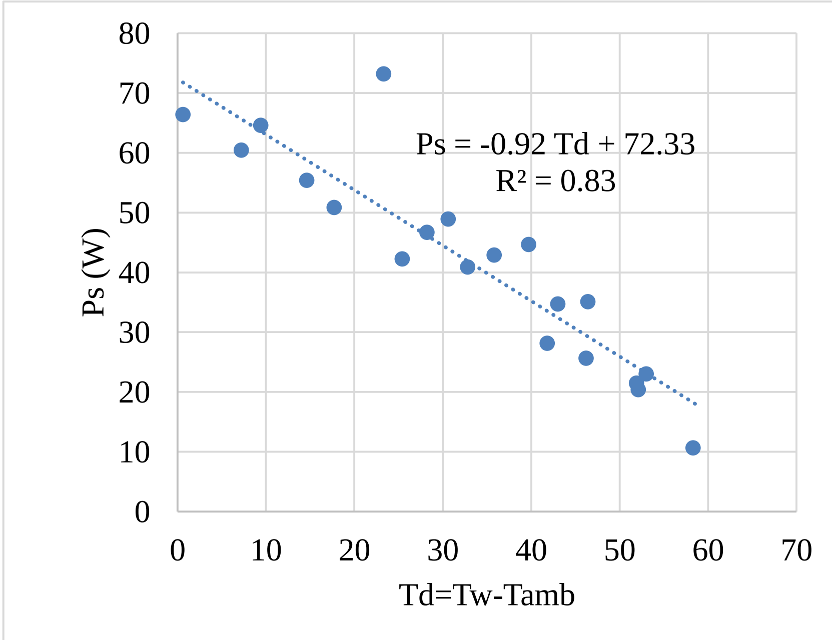

Figure 6. Normalized cooking power as a function of temperature difference.

In addition to the parameters evaluation, a test with five eggs omelet and 0.5 kg of rice cooking were carried out. The eggs were fried within 30 min from 9:00 to 9:30 while 0.5 kg of rice was cooked in 1 h 45 min (from 10:45 to 12:30).

3.4. Estimation of the average stagnation temperature and the cooking time.

From the local metrological data (ambient temperature and mean solar radiation presented in table 2), the mean stagnation temperature and the cooking time of the cooker were estimated and presented in Figure 7. The mean stagnation temperature $\overline{T_p}$ is calculated using equation 7 [29].

$$\overline{T_p} = \overline{T_{amb}} + F_1.\overline{I_G} \quad (7)$$

Table 2. Mean stagnation temperature

Months	Mean solar flux ($W.m^{-2}$)	Mean ambient temperature (°C)
January	835.30	25.6
February	784.41	29.6
March	852.52	31.3
April	810.92	33.5
May	730.35	34.1
June	799.96	27.9
July	763.74	28.8
August	731.03	29.1
September	813.65	30.5
October	854.65	29.5
November	846.31	27.6
December	811.04	23.4

Figure 7 shows that the stagnation temperature varies between 139.49 °C (in August) and 160.03 °C (in March) with a cooking time of 2.97 hours and 2.23 hours, respectively. As it can be seen, the designed solar cooker reaches a sufficient temperature for cooking during the whole year in a country like Burkina Faso. The cooking time is found to be less than 3 hours, which time is attractive for such type of solar cooker [29].

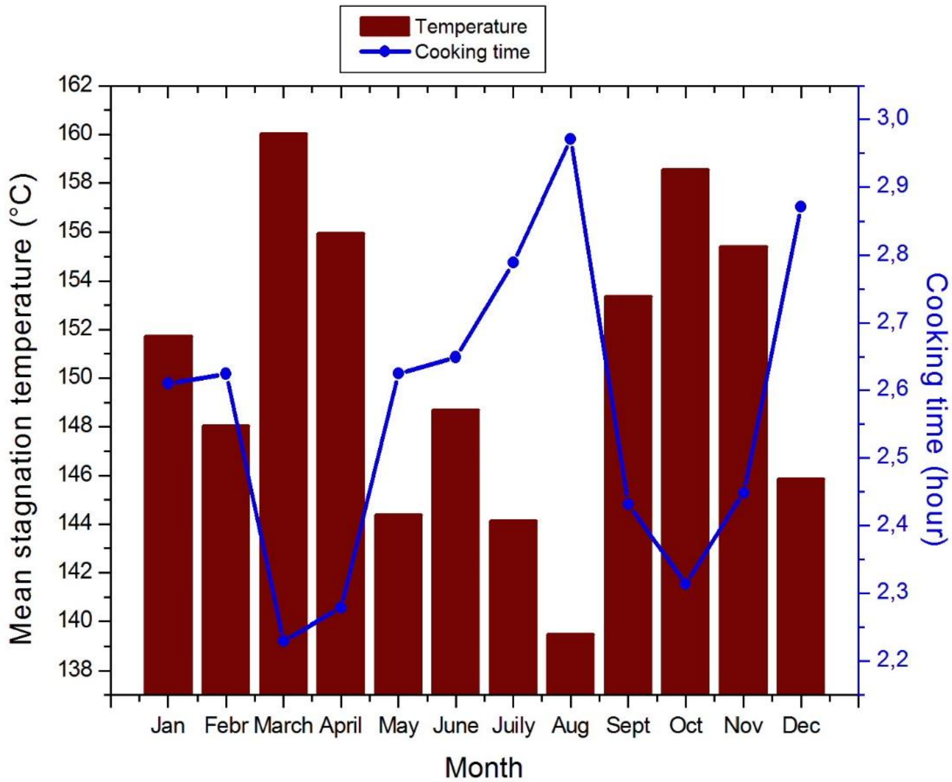

Figure 7. Mean stagnation temperature and cooking time estimated.

Figure 8 shows the average insolation duration obtained by using meteorological data of Ouagadougou from 2014 to 2017. It can be seen that the duration of insolation varies between five (05) and ten (10) hours. Moreover, it can be observed that the insolation is less than six (06) hours during august due to the high frequency of rain. The yearly insolation associated to the cooking time data exploitation revealed that the box-type solar cooker could be used for three hundred and three (303) days/year for an average of four hundred and ninety four (494) meals/year according to the approach developed by Nahar and Gupta [35]. They have demonstrated the possibility of having at least one (01) meal per day for an insolation time greater than six (06) hours and two (02) meals when the insolation time exceeds nine (09) hours/day. The above results suggest that the box-type cooker could be used for covering annually 67.62 % of biomass energy for domestic cooking.

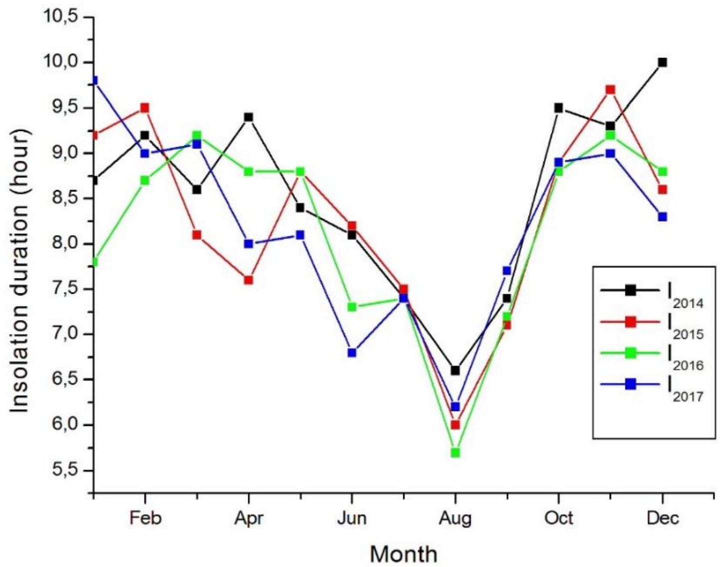

Figure 8. Average duration of insolation from 2014 to 2017.

4. CONCLUSION

In this study, a box-type solar cooker was developed using local accessible materials and tested according to Indian and ASAE standards. The results indicated a good performance of the developed cooker and therefore, promising for a variety of food cooking. Moreover, this shows the opportunity of developing country with high solar irradiation to overcome the domestic energy consumption issues in rural areas while integrating a heat storage unit in the box type cooker system.

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