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Thermal Performance Tests of A Modified Solar Box Cooker

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ABSTRACT
This study reports the thermal performance of a modified solar box cooker at a project site in Dutsin-ma, Katsina state, Nigeria. The hourly variation of five different temperature measurements as well as standard water heating tests and controlled food cooking test carried out during the period of 8th - 12th march, 2018 are also presented. The result of this investigation showed that a maximum temperature of 90 was attained for the water heating tests. The controlled cooking tests results also revealed that the device took 1 hour 30mins and 2 hour 20mins to cook egg and rice respectively. This better performance of the cooker in which cooking speed is higher than that was constructed in 2010 is predicted to be due to the black paint applied to the entire inner surface of the solar box cooker. It is therefore recommended that this device should be used as a cooking device and alternative to firewood.
Keywords: thermal performance, solar box cooker, cooking tests, heating tests

INTRODUCTION

Numerous analytical, numerical and experimented studies on novel designs of solar cookers have been carried out by many researchers. Today solar cooking technology is very promising with its potential in order to narrow the gap between renewable and conventional power sources.

Bello et al, (2010) assert that in almost all the rural homes in Nigeria, the traditional and most popular sources of energy for cooking is firewood. The demand for fire wood leads to the indiscriminate cutting down of trees which in turn leads to deforestation; the attendant ecological hazards attributed to deforestation are glary obvious which encompasses erosion, desert encroachment etc which indeed are particularly devastating in Nigeria. Also the use of firewood for cooking produces smoke which irritates the lungs and the eyes and can cause diseases such as asthma etc. A solar cooker is powered by energy from the sun and can be used as an alternative cooking device so as to reduce the overdependence of the rural people and even many of the urban dwellers on fuel wood.

Nigeria is blessed with an abundant amount of sunshine which has been estimated to be 3,000 hours of annual sunshine (Nyitar, 2013). The project site of this study is Dutsi-ma, a central city of Katsina State which is located in the North western part of Nigeria. The coordinates of Dutsin-ma are: Latitude 12° 27'10"N and Longitude 8° 32'E and altitude 107.4m above sea level (Shamsuddeen 2017).

The city is found in the Sudan Savannah region of the central part of Katsina state which is located in the north western part of Nigeria (NIMET, 2013). Maximum day temperature reaches about 38ºC in the month of March, April and May, and maximum temperature is about 22ºC in December and January (Isa Kaita College of education, weather station). The area receives 900-1000mm of rain annually (Shamsuddeen 2012). The dry starts in late October and usually ends by March, while the rainy season lasts from April to early October (Shamsuddeen 2012).

History revealed a lot of cases detailing the construction of different types of solar cooking devices in Nigeria (Bello, et al 2010; Sambo, et al 1993, Suleiman et al, 2003, Danshehu, 2003, Olajuyi, 2003 as well as Nyitar, 2013). The results of their investigations showed that the working liquids of their solar cookers attained different maximum temperatures which range from 85^0c to 145^0c at 13.00 hours of certain days of investigation. In this project, a modified solar box cooker similar to the one constructed by Bello (2010) has been investigated to evaluate its effectiveness for use as an alternative cooking device.

MATERIALS AND METHODS

Materials used

The materials used for the conduct of this research work are mahogany planks, saw dust, black paint, transparent glass, Plane mirrors, aluminium sheets, crown white wool, glasswool, hinges/rollers, tempered glass, thermocouple, Campbellstokes recorder, PCMs, flat plate, linear focus, central focus collectors, valtzsun photometer pyre geometer, pyradiometer, shading-ring, pyranometer, moving shadow-bar phyrheliometer, black paint, nails, hinges, screws, shelf pins, perforated iron bar, glue, mercury-in-glass thermometer, stop watch screws and inclinometer.

Construction procedure

As earlier mentioned, this work is a modification of the solar box cooker constructed by Bello et al (2010) and other researchers. In the original design only the absorber plate below the box was painted black, the inner walls of the box were left reflecting. However, in this work, the researchers painted the entire inner surface of the box black. A trapezoidal shaped inner box of dimension of 30cm x 30cm x 20cm bounded by an outer box measuring 80cm x 60cm x 30cm was constructed for the study. The two boxes are made from mahogany plank. Aluminium sheet of thickness 0.5mm is glued to the inner box, the aluminium sheet is painted black so that it may significantly retain the heat needed for cooking in the sunny periods, and a heat storage tank for storing phase change chemical material is attached to the inner box in order to store heat from the collectors for cooking at night. Finned absorber plate are used for heat transfer to the food in the cooking vessel, For the insulation of the cooker, saw dust used to fill in the space between the inner and the outer boxes, so also, glass wool and crown white wool are used for insulating the side walls of the cooker and reducing heat losses from the absorbing plate to the environment respectively. For the glazing, two transparent glass panes of thickness of 4.0mm each are fitted on top of the cooker with a space of 10mm between them so that green house effect which is the basis of operation of the solar device is created. A big plane mirror of thickness 4.0mm with measurement of 60cm x 60cm is used as reflector. The reflector consists of wooden frame which was sized to form a cover for the box when not in use. The box was inclined at a suitable angle of inclination to ensure that maximum irradiation falls on it.

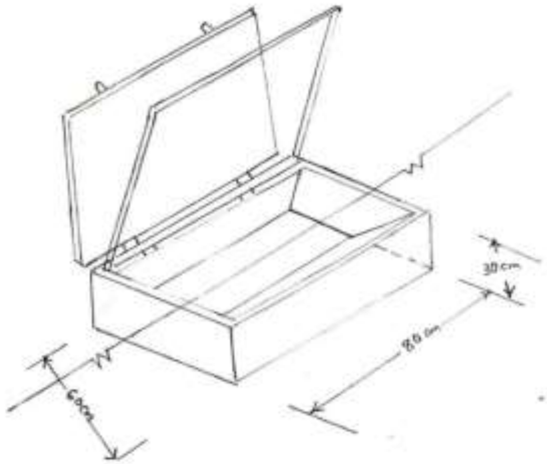

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Fig 1a : Isomeric view of the solar box cooker

Fig. 1b: Inner view of the solar box cooker

Fig.1c: Outer view of the solar box cooker

Principle of operation of Solar Cooker

The operation of a solar cooker is based on the phenomenon/principle of the green house effect. According to this principle, when an energetic short wave solar radiation falls on a glass cover, the glass surface gets heated up. The incident solar radiation I, will then be partly reflected, party absorbed and party transmitted by the glass cover to an absorber plate called a solar collector placed below the transparent cover in accordance with the relation (Idris, 2013):

$$I = r_\lambda + a_\lambda + t_1 \quad (1)$$

Where:

r_λ = reflectivity at a particular wavelength,

a_λ = absorptivity at a particular wavelength and.

t_λ =transmissivity at a particular wavelength.

The transmitted solar radiation is re-radiated by the solar collector to the space between the glass cover and the solar collector (absorber plate) as long wavelength infra-red solar radiation, which is no more able to pass through the glass cover to the atmosphere. Consequently, this trapped solar radiation between the glass cover and the absorber plate is then transferred as thermal energy to the desirable materials like cooking pot and its contents placed on the absorber plate for cooking a required food item or heating water.

Experimental Procedure

The solar cooker was positioned in an open space at Isa Kaita College of Education Dutsin-ma, Katsina State. The thermal system was placed facing southwards where there were no tree shade of any sort so as to maximize the solar radiation falling on it. The cooking device was allowed to heat for about 10 minutes before inserting the load. The device was exposed to direct sunlight to allow incident solar energy fall on it while the reflector was adjusted manually at regular intervals of 30 minutes to ensure that the reflected rays covered the entire glazing surface.

The performance tests conducted were: (i) water heating tests which involves temperature tests that involve temperature measurements connected with photo-thermal system for the period it takes to heat the water as well as (ii) controlled cooking tests. During the experimentation on the cooking and water heating tests, the following temperature readings were observed and recorded:

ambient temperature, T_a

insulator temperature,T_i

working fluid (water) temperature,T_w

absorber plate temperature,T_p and

cooking chamber temperature,T_c.

For the water heating tests, a black painted aluminium pot of mass 0.2kg containing 500cm^3(0.5kg) of water was placed on the absorber plate of the solar box cooker and placed out door for observations. Similarly, for the controlled cooking tests, the food to be cooked plus 750cm^3 of water contained inside the black painted pot were placed in the box and the unit was placed outside for necessary measurements to be observed and recorded. The various temperature and time measurements were measured on hourly basis from 11:00 hours to 17:00 hours using mercury-in-glass thermometers and a stop watch throughout the period of the study.

Mathematical Modeling of Solar Radiation of the Study Site

The study site of this research is Dutsin-ma town. Dutsin-ma town is in the North-Western part of Nigeria. The coordinates of Dutsin-ma are: Latitude 12^{0}27'N Longitude 7^{0}30'E and attitude 106.4m above sea level (NIMET, 2013). The town is located in the Sudan Savanna zone of central part of Katsina state (Shamuddeen, 2012). Maximum day temperature reaches about 38ºC in the month of March, April and May, and maximum temperature is about 22ºC in December and January (IKCOE WS, 2012). The area receives 900-1000mm of rain annually (Atiku and Musa, 1997). The dry starts in late October and usually ends by March, while the rainy season lasts from April to early October (Shamsuddeen, 2012).

In this work, the average global solar radiation value for the months of March and April, 2018 of 45Wm^{-2} (NIMET, 2013) has been used for the estimation of the thermal efficiency of the solar box cooker. The monthly average extraterrestrial radiation in Jth day of the year was computed using the relation (Bello et al, 2010):

$$\overline{H_O} = \frac{24}{\pi} I_{SC}\left[1 + 0.0334\cos\frac{2\pi l}{365} - 3\right] Z \qquad (2) \qquad \overline{H_O}$$

Z= $(Cos\phi Cos\delta Sin\omega_s\delta\text{-}\omega_s Sin\phi Sin\delta)$

$$\delta = 23.45 Sin360\left[\left(\frac{284+j}{365}\right)\right] \qquad (3)$$

Where:

1_{sc}= solar constant taken as $\pm$ 13531.5%Wm^{-2}

J = the Julian day with J = 1st January and 365 on 31st December.

ϕ= latitude of the site of investigation which is Dutsin-ma.

δ= the declination angle of the sun. Usually 15th day of each month is the day on which the solar declination angle, is calculated by Agbo et-al (Agbo et al, 2010) and

ω_s= the sunset hour angle which is given by Olajuyi (Olajuyi, 2003):

$$\omega_s = Cos^{-1}(-tan\phi \; tan\delta) \quad (4)$$

The monthly average of the maximum sunshine hours per day at the location is given by (Olajuyi, 2003):

$$S_{max} = \frac{2}{15}Cos^{-1}(-tan\,\phi tan\,\delta) \quad (5)$$

The monthly average clearness index $\overline{K_T}$ is given by (Abdullahi *et al*, 2013):

$$\overline{K_T} = \frac{H}{H_0} \quad (6)$$

Where $\overline{H}$ is the monthly average global solar radiation on a horizontal surface.

Cooking power of the solar box cooker

The cooking power can be defined as the rate of useful energy available during the heating period and for a standard cooking test, this can be estimated by:

$$p_{sbc} = m.c_p \frac{T_{wf} - T_{Wi}}{600} \quad \text{(Danmallam, 2011)} \quad (7)$$

Where:

F = final

i=initial

w=water

Equation is divided by 600 to account for the number of seconds in each 10 minutes interval as per recommended by Bashir et al, (1999)

RESULTS

The results of the hourly variations of temperature measurements observed in the period of 8th, 9th, 10th, 11th, 12th of March 2018 using the modified solar box cooker are presented in tables 3.1 to 3.5.

Table 2.1: Results of temperature measurements observed with time using the modified solar box cooker on 8th of March, 2018.

Time(Hour)	T_a (°C)	T_i (°C)	T_W(°C)	T_p(°C)	T_c(°C)
11:00	32.5	34.0	28.0	34.0	36.0
12:00	34.5	36.0	53.0	60.0	57.0
13:00	36.0	40.0	70.0	74.0	68.5
14:00	36.5	44.0	82.0	79.0	83.0
15:00	37.0	46.0	81.5	80.0	85.0
16:00	36.0	46.0	79.0	78.0	80.0
17:00	35.0	46.0	75.0	75.0	78.0

Table 2.2: Results of temperature measurements observed with time using the modified solar box cooker on 9th March, 2018

Time(Hour)	T_a (°C)	T_i (°C)	T_W(°C)	T_p(°C)	T_c(°C)
11:00	32.0	32.0	31.0	36.0	34.0
12:00	34.0	34.0	50.0	54.0	52.0
13:00	35.0	38.0	65.0	68.0	64.5
14:00	34.0	40.0	76.0	74.0	78.0
15:00	33.0	40.0	74.5	72.0	76.0
16:00	32.0	40.0	73.0	71.0	74.0
17:00	30.0	40.0	70.0	67.0	71.0

Table 2.3: Results of Temperature measurements observed with time using the modified solar box cooker on 10th March, 2018

Time(Hour)	T_a (°C)	T_i (°C)	T_W(°C)	T_p(°C)	T_c(°C)
11:00	33.0	34.0	30.0	38.0	36.0
12:00	35.0	36.0	51.0	56.0	53.0
13:00	36.0	38.0	64.0	69.0	65.5
14:00	36.0	42.0	77.0	77.0	78.0
15:00	35.0	40.0	75.0	74.0	77.0
16:00	33.0	38.0	72.0	71.5	74.0
17:00	32.0	38.0	69.0	68.0	70.0

Table 2.4: Results temperature measurements observed with time using the modified solar box cooker on 11th March, 2018.

Time(Hour)	T_a (°C)	T_i (°C)	T_W(°C)	T_p(°C)	T_c(°C)
11:00	34.0	32.0	30.0	40.0	39.0
12:00	34.0	34.0	52.0	62.0	60.0
13:00	35.0	38.0	69.0	75.0	70.5
14:00	36.0	42.0	80.0	83.5	86.0
15:00	36.5	44.0	84.5	81.0	83.0
16:00	35.0	44.0	81.0	79.0	81.0
17:00	34.0	42.0	78.0	74.0	79.0

Table 2.5: Results of temperature measurements observed with time using the modified solar box cooker 12th March, 2018.

Time(Hour)	T_a (°C)	T_i (°C)	T_W(°C)	T_p(°C)	T_c(°C)
11:00	32.0	32.0	29.0	40.0	38.0
12:00	33.0	34.0	49.0	52.0	50.0
13:00	35.0	36.0	64.0	68.0	64.5
14:00	36.0	38.0	75.0	72.0	77.0
15:00	34.0	40.0	73.5	70.0	75.0
16:00	33.0	40.0	71.0	67.0	73.0
17:00	30.0	38.0	68.0	64.0	70.0

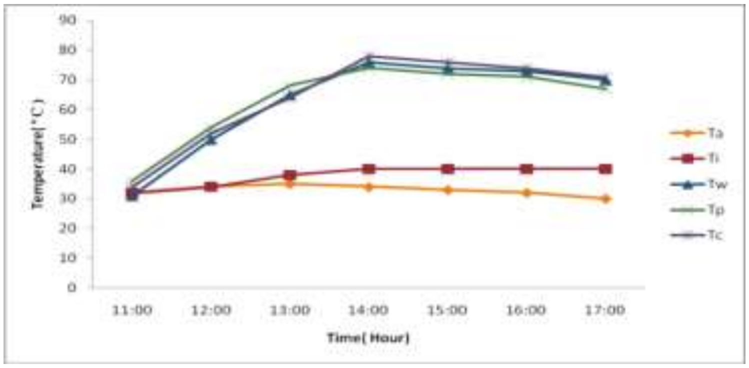


Figure 3.1: Graph of temperature versus Time using the modified solar box cooker on 8th March 2018

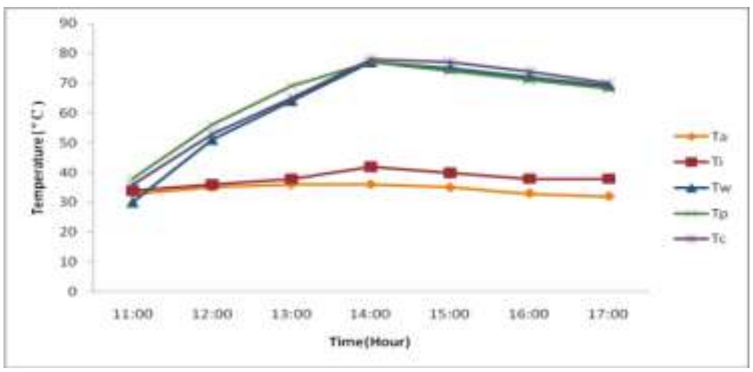


Figure 3.2: Graph of Temperature versus Time using the modified solar box cooker on 9th March 2018

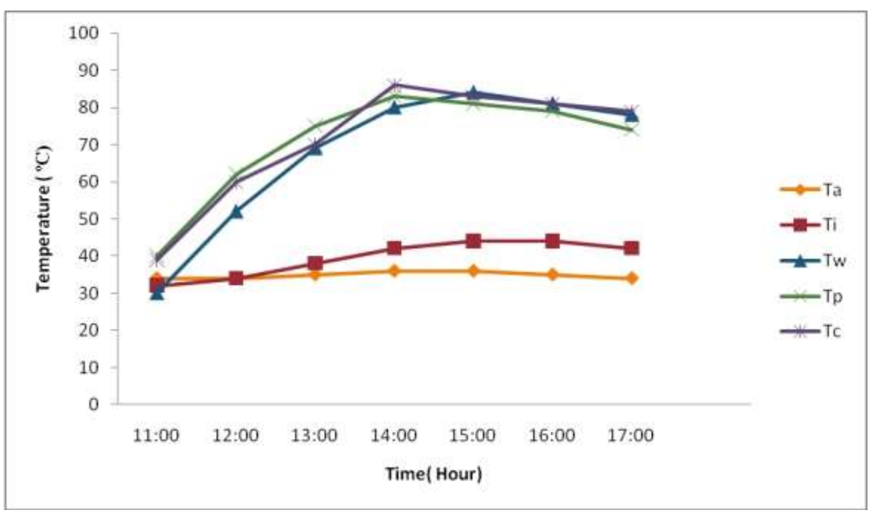
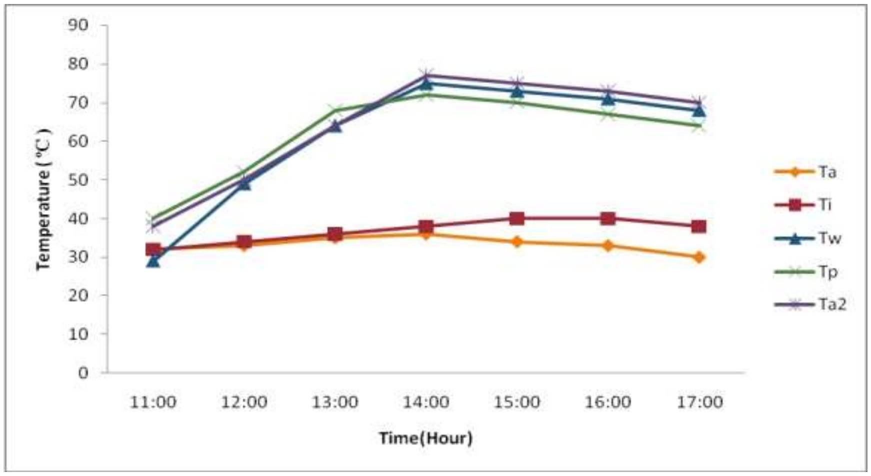
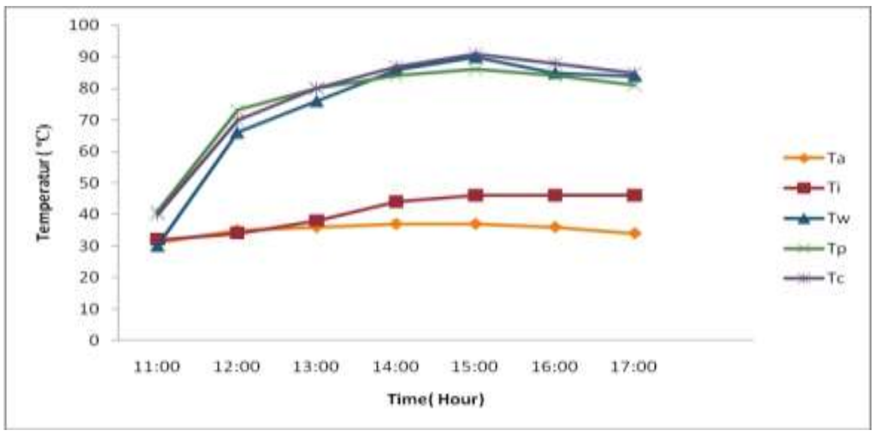


Figure 3.3: Graph of Temperature versus Time using the modified solar box cooker on 10th March 2018



3.4: Graph of Temperature versus Time using the modified solar box cooker on 11th March 2018



3.5: Graph of Temperature versus Time using the modified solar box cooker on 12th March 2018.

DISCUSSION

Figures 3.1-3.5 shows the hourly variations of the ambient temperature (T_a), insulator temperature (T_i), working fluid (water) temperature (T_w), absorber plate temperature (T_P), and cooking plate temperature (T_c) observed for 5 different days of performance tests in the months of March 2018. As shown in the figure 3.1, a maximum temperature of the working fluid of about 82ºC was attained around 14:00 hours (2pm) on this day of investigation in March (08/03/2018). According to figure 3.2 and 3.3, maximum temperature of the working fluid of about 82ºC and 86ºC were attained respectively around 14:00 (2pm) again. On 11/03/2017 (Figure 3.4), it can be seen that a maximum temperature of the working fluid of about 80°C was reached somewhat later in the day around 15:00hours (3pm). However, figure 3.5 shows that a peak temperature of the working fluid of about 90°C was attained. From the results, it can therefore be observed that maximum temperature of the working fluid of about 90°C was attained on the 12th day of the month of the investigation.

In general, it can be observed that, at the early hours of the day, the temperatures increased rapidly. For the second hour, the rate slows down, peak temperatures were mostly attained around 14:00 hours (2pm) in the month. The temperature of the cooker begins to drop gradually after the peak temperature. Also, it is evident that, the differences between the absorber plate temperature, T_p and cooking chamber temperature, T_c is not quite significant. This is possible a reflection of the good emittance and selective surface properties of the absorber plate.

Bello et al (20) reported that the required minimum food cooking temperature is 82°C.The result of the performance tests carried out in this work suggest that, this temperature was attainable during the periods of investigation. This therefore indicates that the constructed solar box cooker is quite good for optimum use during these periods in the Area of study.
After the experimentation on the water heating tests, controlled cooking tests were carried out to examine the effectiveness of the cooker. The device was used to cook egg and rice (0.180kg).The tests were conducted from 11:00 hours 15:hours and it took 1hour 30minutes (11:00am – 12:30pm) to cook egg and 2 hours 20 minutes (12:40 – 3:00pm to cook rice which is comparable to the result obtained by Bello et al (2010)

CONCLUSION

The following conclusions have been made from this study:
The thermal performance evaluation of the modified solar box cooker showed that the cooker can heat water to a maximum of 90ºC which is higher than the value of 88ºC obtained by Bello et al in 2010.
The time taken by the solar device to cook egg and rice (0.180kg) was respectively found to be 1hour 30 minutes and 2 hours 20 minutes while that of Bello et al in 2010 took 1hour 30 minutes and 2 hours 30 minutes to cook the same quantity of egg and rice respectively. This therefore implies that painting the entire inner surface of the solar box cooker black will give a better performance than painting only the absorber plate below box black.
Since this device can cook food in the time stated above, it can be conclude that the device could be used as alternative to firewood for avoidance of indiscriminate cutting down of trees which is the main objective of the research.

RECOMMENDATIONS

Base on the results of this study, the following recommendations are made:
For the better performance of the device, one or more reflectors should be included as part of the cover to increase amount of insulation on the solar collector.
Light materials like plywood should be used to construct the box so as to reduce the weight of the box.
Any future of work of this nature should involve the test of effectiveness of the use of different insulating materials like crumpled newspaper, rice husk or hull, etc to serve as insulators.
More accurate temperature measuring instrument like thermocouple and platinum-resistance thermometers should be used for conducting the various temperature measurement s in future.
Finally, it is recommended that this device should be introduced in to rural areas and urban poor dwellings so as to reduce the felling of trees as sources of fuel woods for domestic cooking and heating of water. This will undoubtedly check the effects of deforestation on our environment

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