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RESEARCH ARTICLE

THERMAL PERFORMANCE ASSESSMENT OF INCORPORATING A BIOMASS COMBUSTION CHAMBER AS A BACKUP SYSTEM IN BOX-TYPE SOLAR COOKERS

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Abstract

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Solar cookers are devices that allow cooking by using free solar energy. However, they can't operate during cloudy periods or at night. Theincorporating of biomass combustion chamber (hybrid cooker solar-biomass) is an alternative that uses an endogenous and renewable energy source for ecological and economical cooking. In this work, the performances of a hybrid cooker (solar-biomass) are evaluated. The experimental results obtained indicate that the absorber plate reached a maximum temperature of 120,62 °C ±1,5°C. Moreover, the maximum power of the cooker was 83.04 W with an efficiency of 30,34 % in solar mode, 28,4 % in biomass mode and 12.27% ±0.002% in hybrid mode. During cloudy periods or in the absence of solar radiation, the use of 0.25 kg of charcoal allows maintaining the absorber temperature around 150°C for more than 2 hours, ensuring continuity of cooking. The first and second figure of merit parameters performed are 0.1043 and 0.2732 respectively. The results obtained are conclusive in both solar and biomass mode.

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Introduction:-

Cooking is an integral part of every human being's life, as food is one of the basic needs of life. In developing countries, common sources of energy for cooking are firewood, crop residues, cow slurry, paraffin, electricity, liquefied petroleum gas (LPG), biogas, etc.(Prasanna, 2010).

Traditional cooking using biomass has negative effects on human health and the global climate. According to the United Nations, two-thirds of the world's population suffer from a lack of wood (Dizier A., 2005.). Approximately two billion people cook over wood fires and live in regions where solar energy can be exploited, such as in Burkina Faso, a sub-Saharan country that benefits from abundant sunshine (3,000 hours of solar radiation per year), with a potential of 5.5 to 6 kWh per square meter per day (World Energy Outlook, 2012). At a time when we are becoming increasingly aware of the effects of climate change, it is essential to consider solar energy as one of the potential alternatives to fossil fuels (Yettou et al., 2017). Solar cooking is one of the possible applications of this energy. Like all cooking systems, solar cooker has several limits as they are dependent on sunlight. Currently, only solar cooker designed to operate outside exist, limiting their flexibility in terms of use. On cloudy days or at night, it is neither practical nor possible to cook with a solar cooker(Mahavar et al., 2017). Several efforts have been done to improve

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the performance of existing cookers, but limitations still persist due to the intermittent of solar energy (Saxena et al., 2012). However, hybrid cooker which harness solar energy with other alternative energy sources such as electricity, gas, or biomass (charcoal, biogas, etc.) can reduce these limitations (Nandwani, 2006). For more flexibility, cost-effective and feasible option, a hybrid cooker (solar-biomass) is an interesting solution which can enable cooking every day of the year , whether it's sunny or cloudy (Quiroga et al., 2019). A hybrid cooker (solar-biomass) is an innovative appliance designed to cook food. This type of cooker is composed of two main parts: A box-type solar cooker and biomass combustion chamber. Work has been carried out on conventional box solar cookers and combustion stoves (Bryden et al., 2006; Cuce & Cuce, 2013; Quiroga et al., 2019; Saxena et al., 2011). But data on the performance of hybrid cookers (solar-biomass) are practically non-existent and particularly in sub-Saharan countries where they can be a very adequate solution.

This work is based on an experimental study of a hybrid cooker (solar-biomass), using charcoal as biomass, whose purpose is to determine its thermal performance.

Materials and Methods:-

Description of the system and measuring equipment

A box-type solar cooker is a device that uses solar energy to cook food. It generally consists of an insulated box covered by transparent glass. This glass allows sunlight to enter the box while blocking heat from escaping.

The realization parameters used for the solar cooker part are based on the work of J. Nébié et al., (Nebie et al., 2019) who determined optimum designed parameters of a solar cooker adapted to Sahelian meteorological conditions.

Under the solar box cooker, a combustion chamber powered by biomass such as charcoal, twigs, wood chips, or other organic materials is integrated. These materials are burned in a controlled manner to generate heat in the absence of solar light.

The combustion chamber contains an air inlet opening. The biomass is placed on grates, and after combustion, the ashes can be collected below the grate. The system is equipped with a chimney for smoke evacuation. The scheme of the hybrid cooker (solar-biomass) is presented on figure 1.

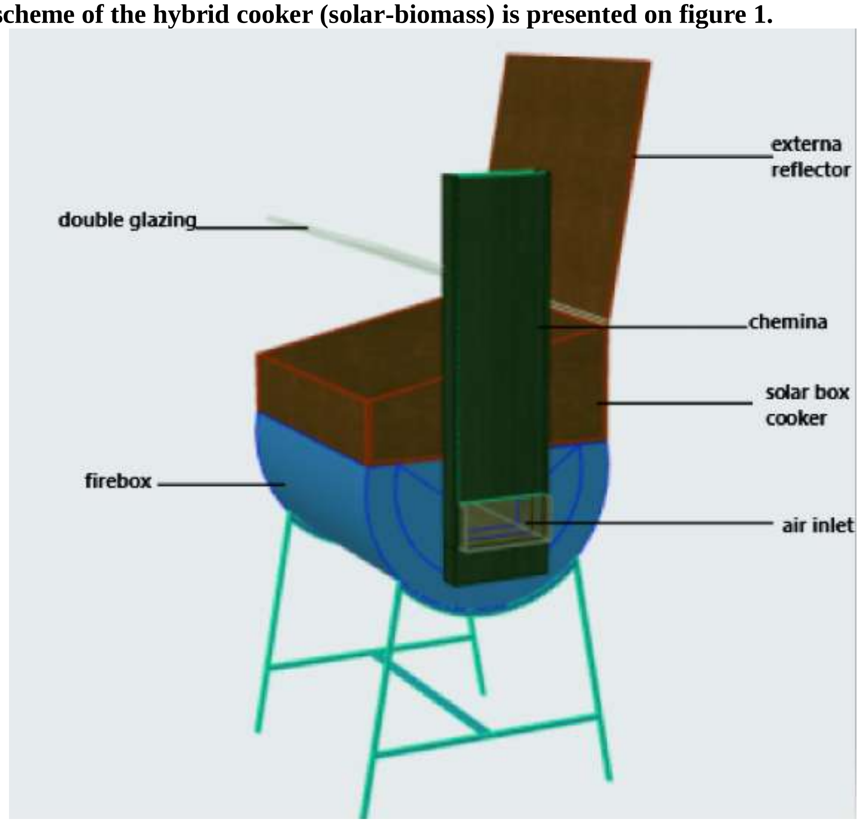

Figure 1:- Scheme of the device.

When the system is used entirely in solar mode, the chimney is removed and the air inlet is completely closed to prevent heat loss.

The thermal performance of the stove was evaluated by doing no-load and load tests. Data acquisition was carried out using a Keithley Datalogger, K-type thermocouples to measure the temperature of the various components and a solarimeter to measure global solar radiation. A CAMRY balance with an error of 0.2g was used to measure the mass of biomass used.

Thermal Performances Assessment

To determine the cooker performances, several methods are available. The most widely used are the Indian standard and the American Society of Agricultural Engineers (ASAE) standard (Yettou F., Azoui B., Malek A., Gama A., 2014).

First figure of merit

The first factor of merit F_1 takes into account the relationship between the optical efficiency of the cooker and the heat it loses to the outside environment from the absorber plate. Experimentally, the cooker was exposed to the sun (clear daylight) from morning to afternoon. Parameters such as ambient temperature, absorber temperature and solar global radiation were evaluated at regular intervals of ten minutes. This figure of merit is calculated using equation

1: (Mullick, S. C., Kandpal, T. C., Saxena, 1987)

$$F_1 = \frac{T_{abs} - T_a}{I_G} \quad (1)$$

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

Second figure of merit

The second factor of merit, F_2 takes into account the efficiency with which heat is transferred to the pan. Quantifying good thermal performance requires good heat transfer to the contents of the container and a low heat capacity of the cooker interior. Thus, the cooking chambermust include a "full load" (container with contents) and be maintained under solar irradiation. The heat transfer between the container and its contents defines the heat exchange efficiency factor, which is indirectly linked to the thermal capacity of the container interior. It is calculated using equation 2 : (Funk, A., 2000.; Mullick S.C., Kandpal T.C., 1997b; ASAE S580 JAN03, 2003.).

$$F_2 = \frac{m_w Cp_w}{A\tau} F_1 ln[\frac{1-\frac{1}{F_1}\left(\frac{T_{wi}-\overline{T_a}}{\overline{I_G}}\right)}{1-\frac{1}{F_1}\left(\frac{T_{wf}-\overline{T_a}}{\overline{I_G}}\right)}] (2)$$

where F_1, Cp_w ,m_w ,T_{wi}, T_{wf} ,$\overline{T_a}$, $\overline{I_G}$ are first figure of merit, water specific heat, mass of water, water initial and final temperature, the average ambient temperature and the average solar irradiation.

Cooking power and energy efficiency

Another figure of interest in solar cookers is the cooking power. It is the main characteristic proposed by ASAE S580 in a cooking process and is a good parameter for evaluating the heating of a solar cooker (ASAE S580 JAN03, 2003). The time interval for measurements is ten minutes as proposed by P. A. Funk. Equation 3 is used to calculate this parameter (A. Funk, 2000).

$$P = \frac{m_w Cp_w (T_{wf} - T_{wi})}{\Delta t} = \frac{m_w Cp_w (T_{wf} - T_{wi})}{600} (3)$$

The thermal efficiency of a solar cooker is the ratio between the energy output (E_{out}) and the energy gained by the cooker (E_{int}) (Mirdha, 2008). In the case of solar energy, the efficiency can be calculated using equation 4.

$$\eta = \frac{E_{out}}{E_{int}} = \frac{m_w Cp_w (T_{wf} - T_{wi})}{Ac.I.\Delta t} (4)$$

In the case of biomass energy, the efficiency can be calculated using equation 5 (IRSAT, 2009).

$$\eta = \frac{E_{out}}{E_{int}} = \frac{m_w Cp_w (T_{wf} - T_{wi})/\Delta t_1 + m_w L_v/\Delta t_2}{m_{comb} ,LCV/.\Delta t} (5)$$

With L_v, m_{comb}, LCV are latent heat of vaporization, mass of charcoal and lower calorific value of charcoal
When solar radiation and biomass combustion are used, the efficiency can be calculated usingequation 6.

$$\eta = \frac{E_{out}}{E_{int}} = \frac{m_w Cp_w (T_{wf\,1} - T_{wi\,1}) + m_w Cp_w (T_{wf\,2} - T_{wi\,2}) + m_w L_v}{Ac.I.\Delta t + m_{comb}\ ,LCV} \quad (6)$$

Results and Discussion:-

Thermal Test in solar cooking mode

Stagnation test (no-load test)

To use the cooker exclusively for solar cooking, the biomass combustion chamber must be removed. Figure 3 shows the cooker with the combustion chamber closed when operating in solar cooker mode.

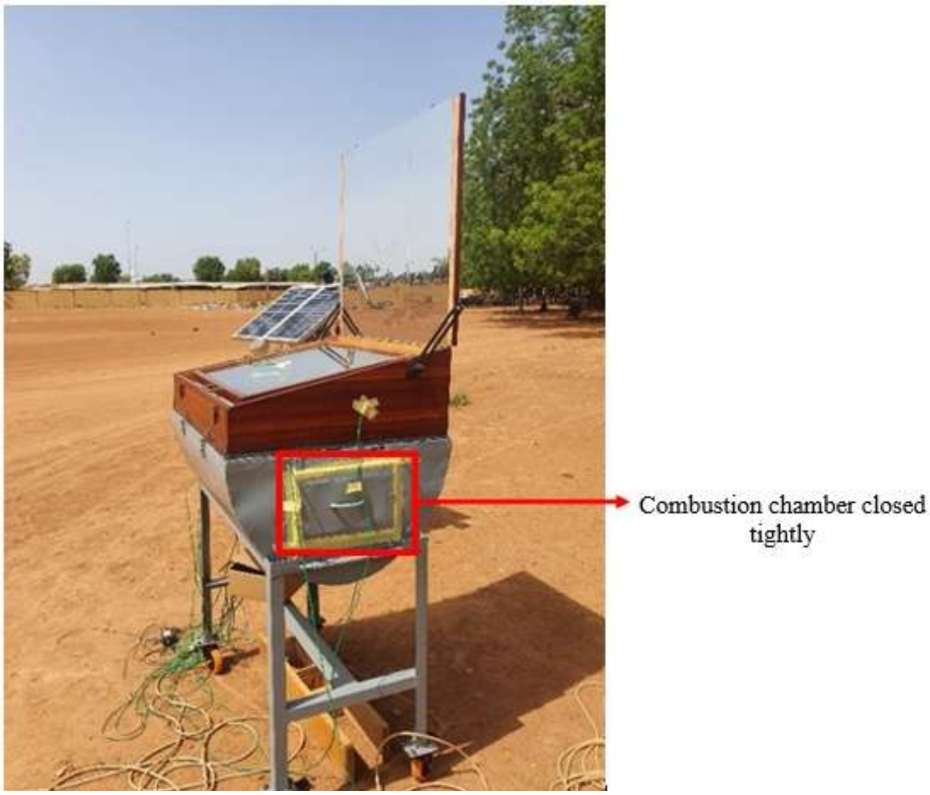

Figure 2:-System in solar cooking mode.

Figure 4 shows the evolution of the absorber, internal air in the cooker and ambient temperature and global solar radiation. The data are recorded at 10 minutes intervals. The absorber temperature rises from 65,55 °C to 101,17 °C$\pm$1,5°C in forty-eight minutes, from10:08 to 10:58. This temperature reaches a maximum stagnation value of 120,62 °C$\pm$1,5°C at 1:08 p.m. with an ambient temperature of 39,88 °C and a global solar radiation of 907,33 W.m^{-2}$\pm$45,36 W.$\mathbf{m^{-2}}$. The temperature remains above 100 °C until 16:06. Global solar radiation reaches its peak 2 hours before that of the absorber temperature. This phase difference is due to the thermal inertia of the cooker. However, the maximum stagnation temperature of the absorber is adequate for cooking food (Mullick, S. C., Kandpal, T. C., Saxena, 1987). According to the literature, the maximum temperature reached with a hybrid cooker is around 120 °C (Quiroga et al., 2019). This result is appreciable because several simple solar cookers encountered in literature have temperatures of the same order (G. Guruprasad, 2020; H. Kurt, 2008; R. Misra and T. Kumar Aseri, 2012).

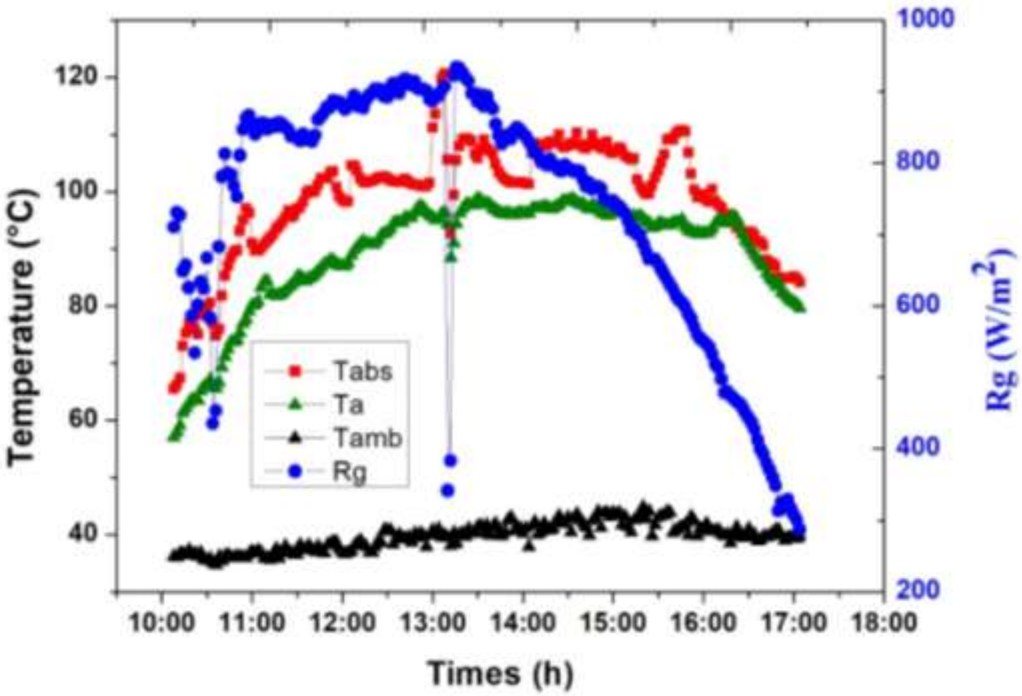

Figure 3:- Time evolution of the absorber temperature (Tabs), the ambient temperature (Tamb), the internal air temperature (Ta) of the cooker and the global solar irradiation (Rg).

Test with Load

In this test the cooker is loaded with 1.5 kg of water into an aluminum pan. After exposure to solar radiation for 1 hour (from 9 h 37 to 10 h 37), the water temperature reached, 86,32 °C± 1,5 °C (Mullick SC., Kandpal TC., 1997a).

The maximum temperature of 98,04 °Cwas reached at 11:27a.m. and remained practically constant for over 4 hours, as shown in figure 4. Most cooked foods have a high-water content, and the cooking temperature required varies from 90 to 100 °C (S, Nandwani, 1996).

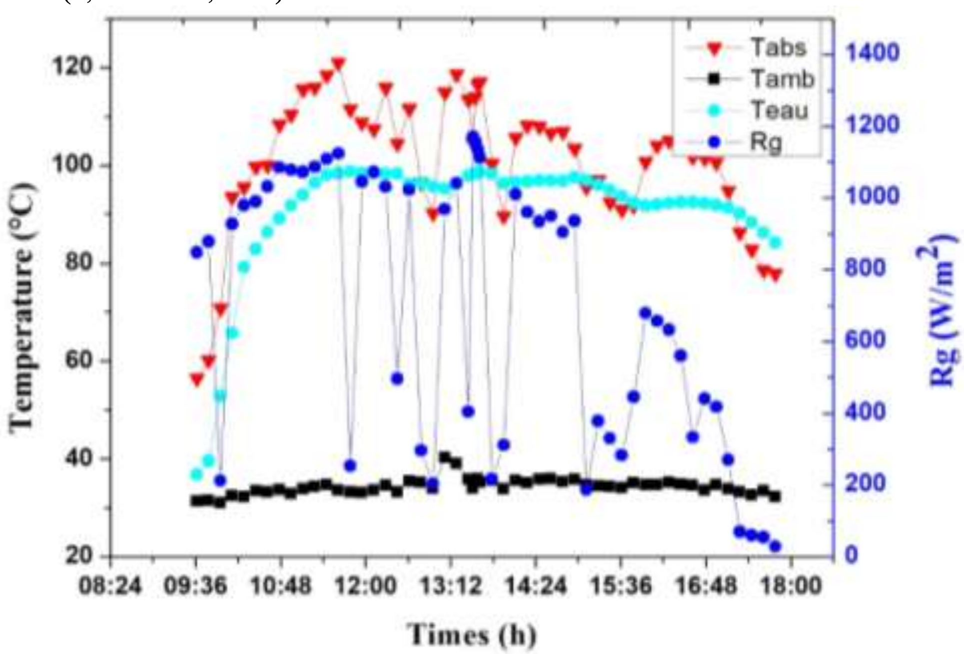

Figure 4:- Time evolution of the absorber (Tabs), glazing (Tv1), internal air (Ta), water (Teau), and ambient temperatures (Tamb) and global solar irradiation (Rg).

Fluctuations in the solar radiation curve indicate the presence of clouds, which affect the absorber temperature as well as the water temperature.

From 11 h 47 min the clouds passed through repeatedly. During this period, the absorber temperature falls from 120.95°C to 77.79°C, while the water temperature falls from 98.73°C to 84.16°C.

The passage of clouds is a handicap to the efficient operation of the cooker.

When the sky is covered in clouds, it acts like a black body at a temperature well below that of the absorber, resulting in significant heat loss by radiation to the sky.

The no-load and load results obtained show that the cooker realized is capable of cooking in the weather conditions of Sahelian regions.

However, to compensate for the fall in temperature due to cloud fluctuations, Nébié et al. used Jatropha crude oil as a heat storage system.

They showed that in the event of a cloud disturbance, this fall in absorber temperature is limited to the temperature of the storage oil. So, there is effectively a transfer of heat from the storage to the absorber thanks to the Jatropha oil.

This also shows that storage minimizes the effect of passing clouds on the operation of the solar cooker for a certain period of time(Ki-ZERBO& Nebie, n.d.).

Once the energy stored in the Jatropha oil has been discharged, cooking with the solar cooker becomes complicated in the absence of solar energy, hence the need for an alternative energy source to ensure continuity of service at all times.

Thermal test in biomass mode

To operate the cooker exclusively in biomass mode (on cloudy days or at night), the biomass combustion chamber must be inserted with the chimney. Figure 5 shows the cooker with the chimney used when operating exclusively in biomass mode.

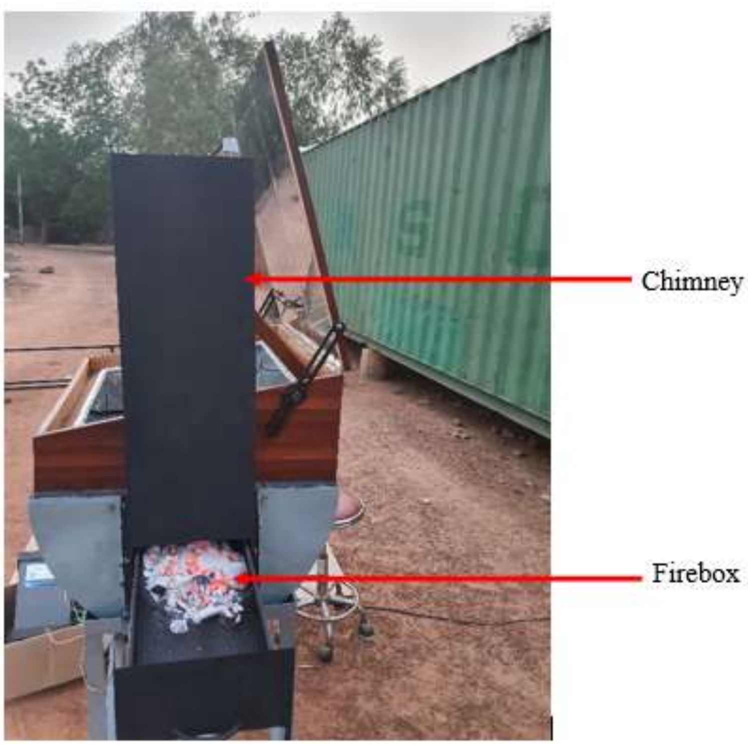

Figure 5:-Cooker with combustion chamber used when operating in biomass mode only.

No-load test

Figure 6 presents result in biomass mode shown. The combustion chamber is loaded with 0.5 kg of charcoal. The combustion temperature rises from 35 to 300.89 °C in 46 minutes after the combustion started. While the absorber temperature rises from 34 °C to 100 °C in 17 minutes from the start of the test, decreasing with the combustion temperature after 1 hour of testing. Absorber temperature remains above 100 °C for around 2 hours.

The combustion temperature is the highest, followed by the absorber temperature, as a large part of the energy is transferred to the absorber due to the insulation of the walls and the fact that combustion takes place just below the absorber.

These results indicate that combustion is proceeding well due to the thoughtful design of the combustion chamber, which enables proper ventilation of the combustion process.

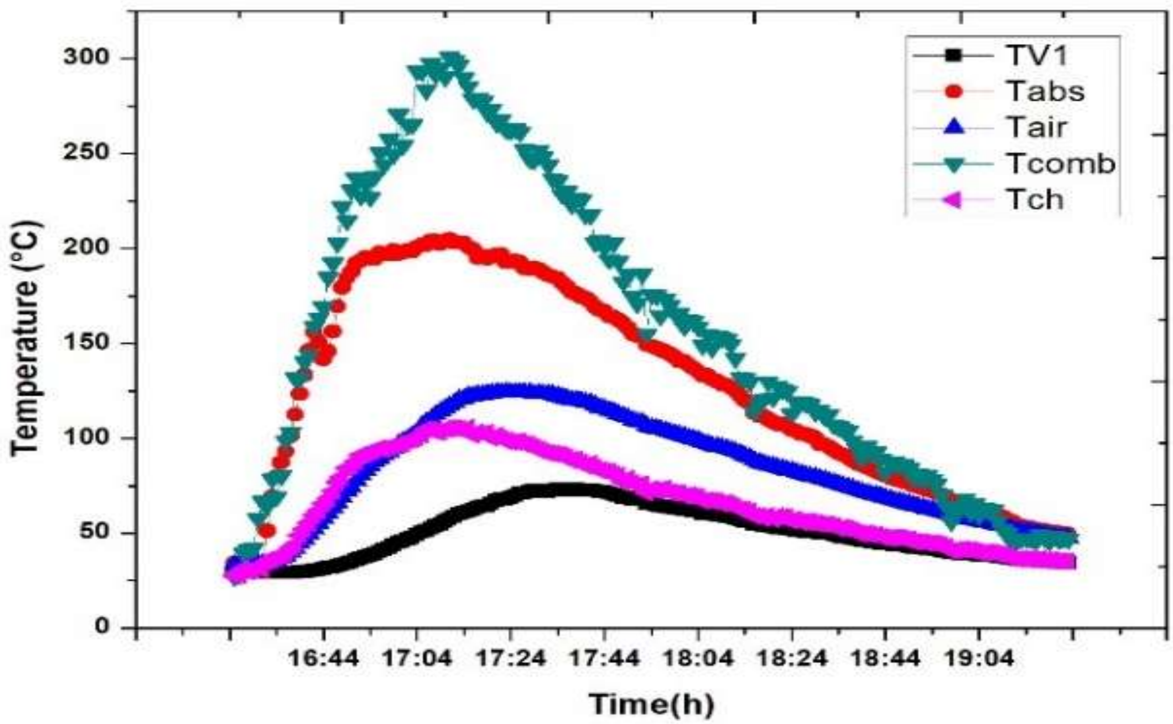

Figure 6:- Time course of combustion temperature (Tcomb), absorber temperature (Tabs), glass 1 temperature (Tv1), indoor air temperature (Tair) and cooker chimney temperature in biomass mode.

Test with Load

Figure 7 shows the results obtained when heating the same quantity of water (1kg) in biomass mode. The same mass of charcoal, 0.5 kg, is used in the combustion chamber. After 30 min (from 17:10 to 17:40), the water temperature reached a maximum of 100 °C. The temperature remains constant for over 2 h 30 despite the drop in absorber temperature related to the fuel depletion. The temperature reached and the time taken are well suited to cooking in sub-Saharan countries (Ndayisenga, 1994). A considerable difference between the combustion temperature and the others temperatures is observed. This is due to the presence of the load, which takes part of the energy released by combustion. This is due to the fact that when the water reaches its vaporization temperature, the energy received is used to vaporize the water and the temperature remains constant around the vaporization temperature (around 100 °C under the experience conditions).

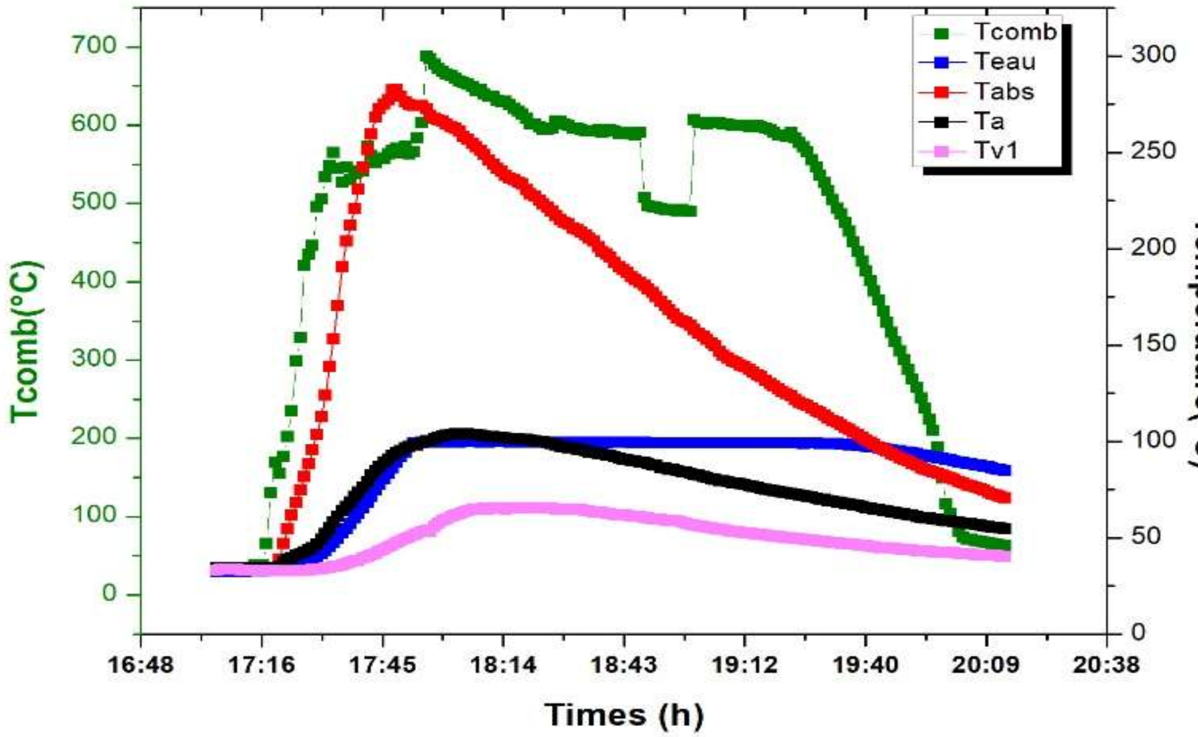

Figure 7:- Temporal evolution of combustion temperature (Tcomb), absorber temperature (Tabs), glass 1 temperature (Tv1) and water temperature (Teau) of the stove in biomass mode.

The combustion temperature in the no-load test is higher than the combustion temperature in the loaded test due to the air flow at the combustion chamber inlet. Indeed, when wind speed is high, the air flow at the combustion chamber is high, increasing combustion temperature.

Thermal test in hybrid mode

The experimental study in hybrid mode is based on a no-load test and a load test, as in the case of the experimental study in solar mode and biomass mode.

No-load test

A number of no-load tests are used to determine the contribution of biomass combustion when there is insufficient solar radiation to ensure efficient cooking.

Figure 8 shows the results obtained for the test run of the cooker in hybrid mode.

The thermal test is done by first starting the cooking process using the solar energy present (step 1), then opening the combustion chamber to place the container of embers and the chimney when the solar energy present is no more sufficient to ensure the continuity of the cooking process (step 2), and finally, the cooking process continues with the combustion of the biomass as the energy source (step 3).

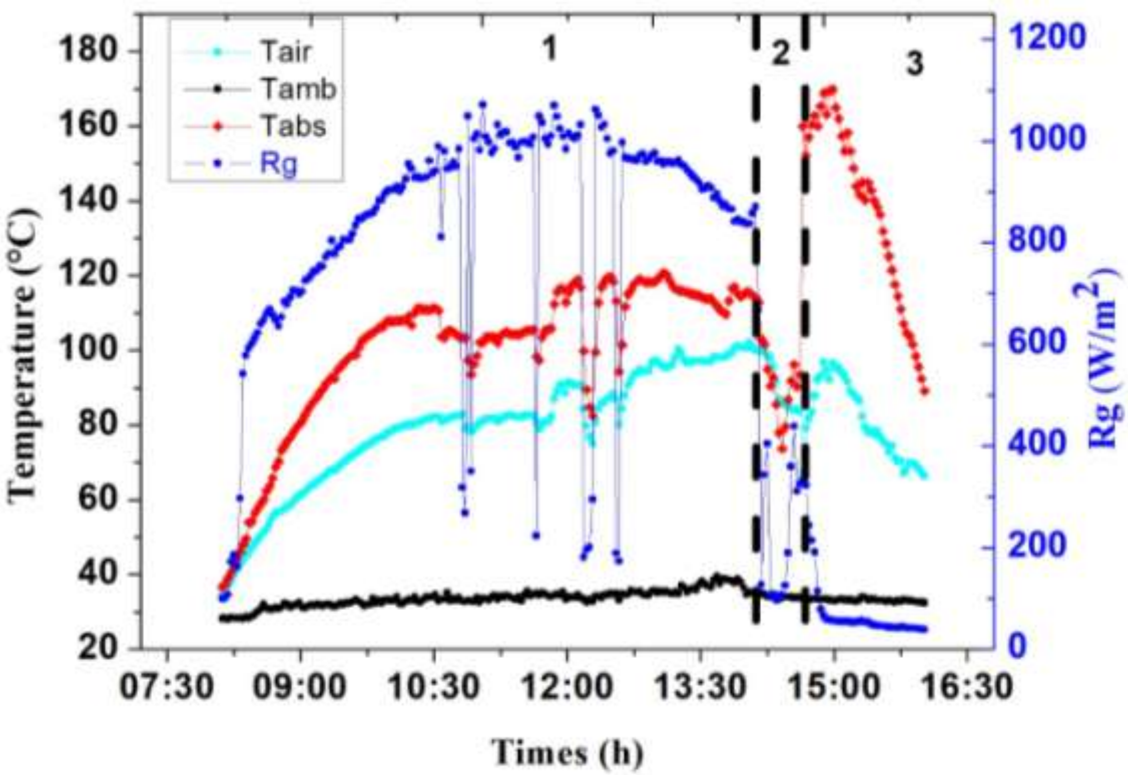

Figure 8:- Time evolution of the absorber temperature (Tabs), the ambient temperature (Tamb), the internal air temperature (Ta) of the cooker and the global solar irradiation (Rg) in hybrid mode.

The absorber temperature rises from 36.57°C to 100.62°C at 1 hour 31 minutes, from 08:07to 09:39, and reaches a maximum temperature of 120.71°C at 13:05 under global solar radiation of 954.74 W/m^2 with an ambient temperature of 35.17 °C. At 14:11 on, solar radiation becomes low (<600 W/m^2) to ensure the efficient operation of the system, the combustion support is inserted between 2.15pm and 2.23pm, to load 0.25kg of biomass (charcoal embers) into the combustion chamber. During the loading of coal into the combustion chamber, the temperature of the absorber drops considerably to 73°C. When the coal embers were loaded into the combustion chamber, the temperature in the absorber increased rapidly, reaching 159.88°C at 2.39pm, 16 minutes after the coals were loaded. It continued to rise until it reached a maximum value of 169.86°loaded. It 2:59pm. The 0.25 kg of fuel loaded kept the temperature of the absorber above 100°C until 4.01pm, i.e. for more than 1 hour and 22 minutes.

The combustion system also operates as a heat source when solar radiation is low. For utilization in hybrid mode, 0.25 kg of coal is sufficient to maintain service for almost 2 hours, compared with the 0.5 kg required for biomass mode, which also saves biomass.

Test with load

In this test the cooker is loaded with 1.5 kg of water into an aluminum pan. The 1.5 kg load of water is integrated after the cooker has been exposed to the sun until the absorber reaches a temperature of 80.3°C with a global solar radiation of 874.06 W/m^2.

The weather was affected by a cloudy disturbance from 11.14am, as indicated by the fluctuations in the solar radiation curve.

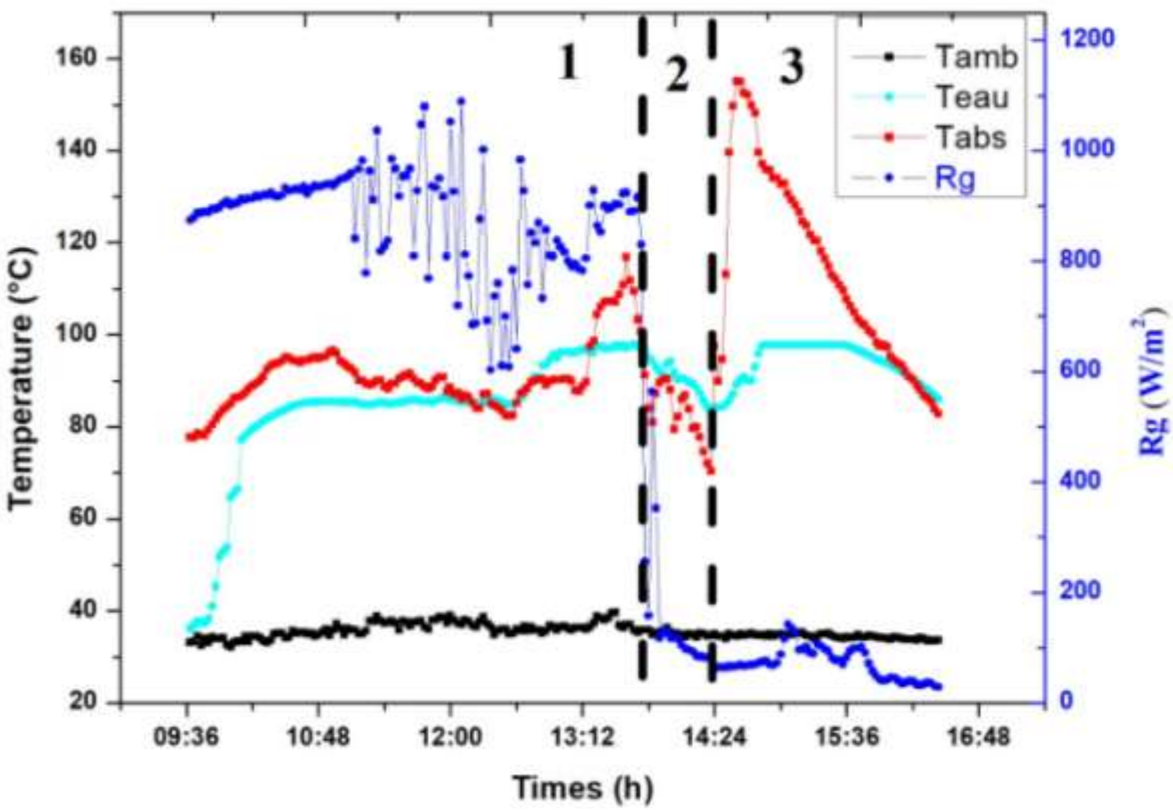

Figure 9:- Time evolution of the absorber (Tabs), water (Teau), and ambient temperatures (Tamb) and global solar irradiation (Rg) in hybrid mode.

The water introduced into the cooker at 09:38 reached a temperature of 85°C at 10:38 in solar radiation of 928.75 W/m² and continued to rise, reaching 97°C at 12:58. The temperature remained close to 100°C until 13:44. As the solar radiation decreased and the combustion chamber opened, the water temperature fell, reaching 85.71°C at 2.18pm. Although the combustion chamber was opened, the temperature remained above the cooking time (85°C). After inserting the coal (0.25 kg), the temperature of the water began to rise again until it reached boiling point and remained close to this value until the end of the tests (from 2.48pm to 4.38pm), i.e. 1 hour 50 minutes of boiling. The energy contribution from the biomass enabled the water to maintain its boiling temperature despite the considerable decrease in solar radiation, demonstrating that during solar cooking, in the event of a fairly long period of cloud cover, the biomass can ensure the continuity of cooking with 0.25kg of charcoal for approximately 2h54min more cooking time (13h44 min to 16h 38 min).

Performance results

3.3.1 Calculate the "First and Second figure of merit" parameters F_1 and F_2

Table 1 shows the different F_1 and F_2 values obtained in solar mode.

These parameters are determined from equations 1 and 2 respectively.

Tableau 1:- First and Second figure of merit results.

Performance parameters	Parameter values
F_1(m^2C/W) (solar mode)	$\mathbf{0{,}1043 \pm 0, 006}$
F_2(SI) (solar mode)	$\mathbf{0{,}2732 \pm 0, 012}$

Table 1 shows that the first figure of merit F_1 is 0.1043 m^2°C/W in solar cooker mode. This value is in the same range as the values found in the literature for a hybrid cooker in solar mode (Quiroga et al., 2019).

To confirm this performance, the second figure of merit was evaluated using equation 2 for solar mode F_2= 0.2732. This value, which lies between 0.254 and 0.490, indicates that the cooker model has a high heat exchange factor, leading to a good heat transfer during solar cooking mode (Mullick S.C., Kandpal T.C., 1997a).

Calculate power and thermal efficiency

The power and thermal efficiency per hour of the cooker obtained in solar mode are shown in Figure 10. These parameters are determined from equations 3 and 4 respectively.

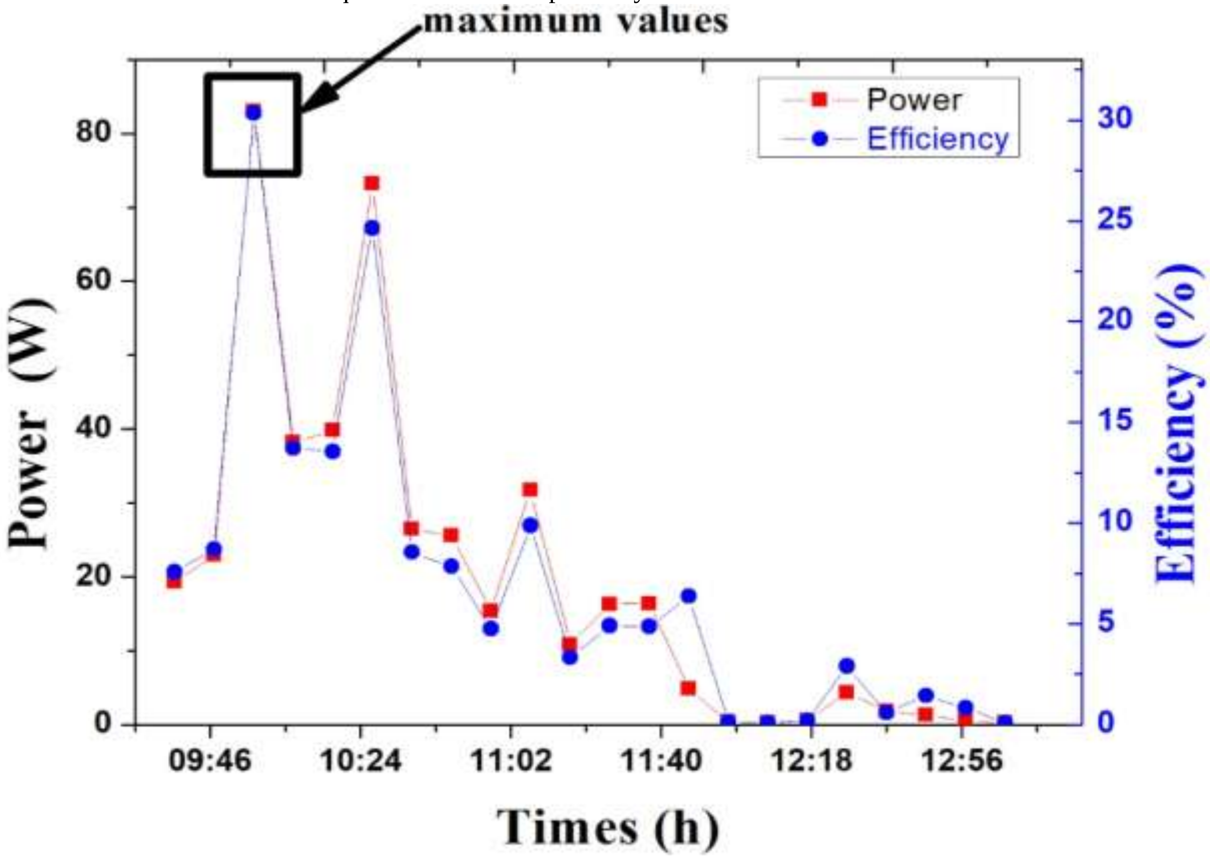

Figure 10:- Power and thermal efficiency in solar mode.

The power and thermal efficiency of the cooker in solar mode increase as solar radiation increases at the start of the experiment, reaching their respective maximum values in each case, then gradually decrease until they reach zero. This reduction in power and efficiency is due to the fact that the temperature of the water rises slowly as it approaches boiling point. At this temperature, power and efficiency become zero because the water temperature remains constant. The maximum cooking power is 83.04 W with an efficiency of 30.34% when operating in solar mode. In fact, the cooking power shows that the cooker in solar mode provides the necessary heat for the food to be cooked. Nébié et al obtained a maximum power of 84 W for the tests on 29/02/2020 and 73.20 W on 20/03/2020(Ki-ZERBO& Nebie, n.d.).The solar mode efficiency results are also interesting in that the results obtained are in the same range as those in the literature, since the efficiency of several box-type solar cookers mentioned in the literature varies from 3.05% to 35.2%(HH, 2004), (A. Aremu, 2014).The results show that the system works well despite its complexity.

Table 2 shows the calculation of the thermal efficiency in biomass mode and in hybrid mode of the cooker.

Tableau 2:- Results of thermal tests in biomass and hybrid mode.

Performance parameters	Parameter values
Biomass mode efficiency (%)	**28,4$\pm 0,0015$**
Hybrid mode efficiency (%)	**12,27 $\pm 0,002$**

Table 2 also shows that the maximum thermal efficiencies of the cooker in biomass mode and hybrid mode are 28.4% ±0.0015% and 12.27% ±0.002% respectively.

For operation in biomass mode, the operating efficiency was determined using equation 5. In the literature, the efficiency of traditional stoves is between 15 and 19%, that of improved natural convection stoves between 16 and 27% and that of forced convection stoves between 30 and 35%(R. Suresh, V. Singh, J. Malik, A. Datta, 2016).

These results show that the device used in this work, operating in biomass mode using simple natural convection, gives results in line with other cookers thanks to the thermal insulation and adequate ventilation of the combustion chamber, since all the energy generated by combustion is directed towards the absorber.

The thermal efficiency of the cooker in hybrid mode is calculated using equation 6.

In hybrid mode, the efficiency of cookers is relatively low. This is because the system uses two sources of energy to achieve its objective, resulting in an increase in the input energy required to obtain the same output energy as that obtained in cooking modes using biomass or solar energy alone.

The thermal efficiency of our system, which is 12.27% ±0.002% in hybrid mode, shows that the cooker performs quite well when compared with the thermal efficiencies of other hybrid cookers in hybrid operation.

Quiroga et al. evaluated the thermal performance of their model of hybrid solar-biomass cooker. In hybrid operation, they obtained an efficiency of 5.8%(Quiroga et al., 2019).

Bisrat Yilma Mekonnen et al. are developing a hybrid cooker model which is a box-type cooker equipped with a reflector placed on a combustion hearth. This system uses the energy from the furnace as a back-up system when there is no sun. They have achieved a thermal efficiency of 5% when operating in hybrid mode(Coulson & Ferrari, 2019).

Conclusion:-

This study shows that the hybrid system combining solar energy and biomass for cooking can reduce daily fuel consumption by using free solar energy and cooking independently of the season, since biomass can be used for cooking when solar energy is not sufficient.

The stagnation temperature, which is 120,62 °C$\pm$1,5°C, is sufficient for cooking. The hybrid cooker gives an efficiency of 30.34% in solar mode,$28{,}4\pm0{,}0015$in biomass mode, and $12{,}27\pm0{,}002$ in hybrid modewith a cooking power of 83.04 W in solar mode. These tests showed that when there is no sunlight at all, using the cooker in biomass mode means you can cook for 3 hours using 0.5 kg of charcoal. On days when the sun shines for a while and then disappears, 0.25 kg of charcoal can be used to cook for 2 hours in hybrid mode. The results obtained are conclusive in both solar, biomass and hybrid modes. The widespread use of this system will contribute to the fight against climate change. Smoke emission analyses will be conducted to assess the real environmental impact of this system. Studies need to be conducted to control the airflow rate entering the combustion chamber which impact significantly the combustion temperature.

Nomenclature

Eout: energy out (W)
Ein: energy int (W)
IG: solar global irradiation (W/m²)
$\Delta t=t_2-t_1$: time interval from Twi to Twf (s)
Ta: ambient temperature (˚C)
Twi: water initial temperature (˚C)
Tw: water final temperature (˚C)
m_w: water mass (kg)
m_{comb}: combustible mass (kg)
c_w: specific heat capacity of water (J/kg K)
LCV: Lower calorific value (kJ/kg)
L_v :latent heat of vaporization (j/kg)
P: cooking thermal power (W)
η: energy efficiency of the cooker
Ac: opening area of the solar cooker (m2)

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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