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Realization and Experimental Study of a Hybrid Cooker (Solar-Biomass) in a Sahelian Climate

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ABSTRACT

Solar cookers are devices that allow cooking by using free solar energy. However, they can't operate during cloudy periods or at night. A 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 121.60 °C. Moreover, the maximum power of the cooker was 78.47 W with an efficiency of 29 % in solar mode and 28.4% in biomass mode. The first and second figures of merit parameters performed are 0.1043 and 0.2732 respectively. The results obtained are conclusive in both solar and biomass mode.

Keywords: Hybrid cooker, Solar energy, Biomass, Local materials, Eco-friendly

1. Introduction

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 suffers 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, the solar cooker has several limits as they are dependent on sunlight. Currently, only solar cookers 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 made to improve the performance of existing cookers, but limitations still persist due to the intermittent solar energy (Saxena et al., 2012). However, hybrid cookers 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 a more flexible, 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 a 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). However, data on the performance of hybrid cookers (solar-biomass) are practically non-existent, 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.

2. Materials and Methods

2.1 *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. The detailed parameters of the solar cooker designed for the present studies are shown in Table 1.

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. For the design of the combustion chamber, we use the design principles of Dr. Larry Winiarski, which have been adopted by numerous organizations to create efficient combustion chambers(Winiarski, 2005). Winiarski's design approach combines both clean combustion and optimized heat transfer features (Winiarski, 2005). From these principles, the combustion chamber has been constructed using the dimensions presented in Figure 1.

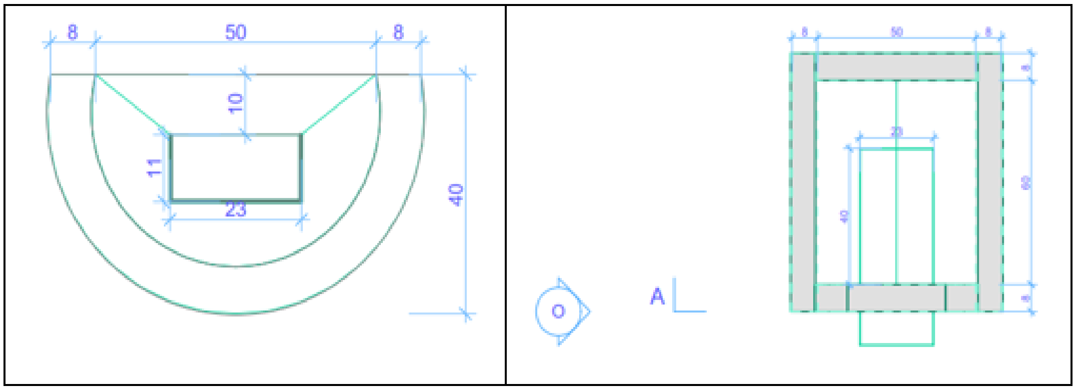

Figure 1: dimensions of the combustion chamber

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 in Figure 2.

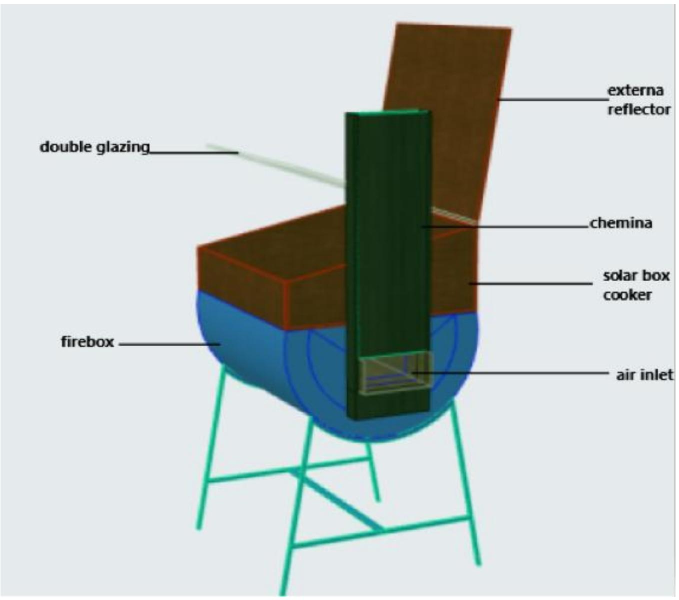

Figure 2: Scheme of the device

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.

Tableau 1: Design parameters of the cookers

Component	Dimension	Materials
Inter Solar box	60cm x 50cm x 15 cm 30 cm	Plywood
Outer Solar box	70 cm x 60cm x 15cm 30cm	Plywood
Double glazing	60cm x 50cm	5 mm inter-thick glass and 4 mm outer thick glass
Reflector	70 cm x 60cm	S-reflect
Absorber plate	60cm x 50cm	Black coated aluminium
firebox		aluminium sheet
firebox insulation		compressed earth bricks

2.2 *Thermal Performances Assessment*

To determine the cooker's performance, 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).

2.2.1 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)

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

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.

2.2.2 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 chamber must 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.).

$$F_2 = \frac{m_w Cp_w}{A\tau} F_1 ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{wi} - \overline{T}_a}{\overline{I}_G}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{wf} - \overline{T}_a}{\overline{I}_G}\right)}\right] \qquad (2)$$

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

2.2.3 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).

$$P = \frac{m_w Cp_w (T_w^i - T_w^{i-1})}{\Delta t} = \frac{m_w Cp_w (T_w^i - T_w^{i-1})}{600} \quad (3)$$

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.

$$\eta = \frac{E_{out}}{E_{int}} = \frac{m_w Cp_w (T_w^i - T_w^{i-1})}{Ac.I.\Delta t} \quad (4)$$

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

$$\eta = \frac{E_{out}}{E_{int}} = \frac{m_w Cp_w \left(T_w^i - T_w^{i-1}\right)/\Delta t_1 + m_w L_v/\Delta t_2}{m_{ch}, PCI/.\Delta t} \quad (5)$$

With L_v, m_{ch}, PCI are latent heat of vaporization, mass of charcoal and lower calorific value of charcoal

3. Results and discussion

3.1 Thermal Test in solar cooking mode

3.1.1 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.

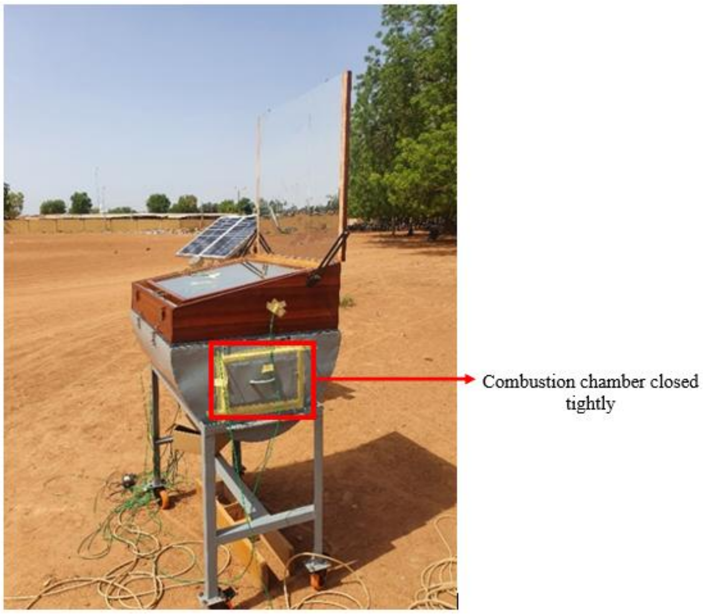

Figure 3: system in solar cooking mode

Figure 4 shows the evolution of the absorber, internal air in the cooker's ambient temperature and global solar radiation. The data are recorded at 10-minute intervals. The absorber temperature rises from 65.5 °C to 100.2 °C in one hour thirty-two minutes, from10:06 to 11:38. This temperature reaches a maximum stagnation value of 121.60 °C at 2:46 p.m. with an ambient temperature of 35.8 °C and a global solar radiation of 945.7 W/m². The temperature remains above 100 °C until 16:48. 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).

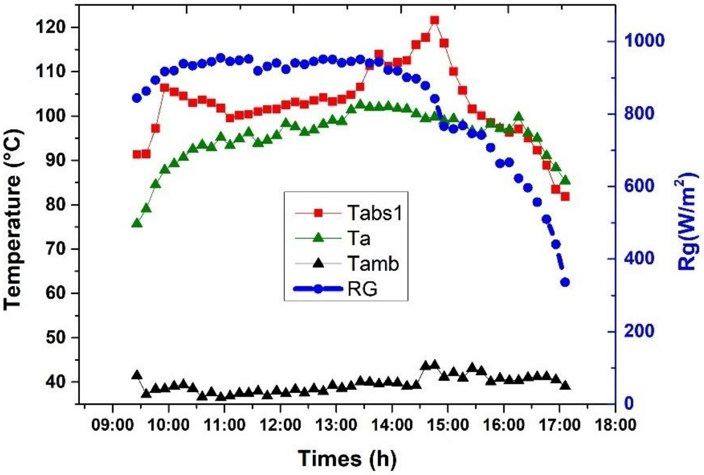

Figure 4: Time evolution of the absorber temperature (Tabs), the ambient temperature (Tamb), the internal air temperature (Ta) of the cooker and the global solar irradiation (Rg)

3.1.2 Test with Load

In this test, the cooker is loaded with 1 kg of water into an aluminium pan. After exposure to solar radiation for 2 hours 52 minutes (from 8 h 45 to 11 h 37), the water temperature reached, 90.12 °C (Mullick S.C., Kandpal TC., 1997a).

The maximum temperature of 99 °C was reached at 3:45 p.m. and remained practically constant for over 4 hours, as shown in Figure 5. Most cooked foods have a high water content, and the cooking temperature required varies from 90 to 100 °C (S, Nandwani, 1996).

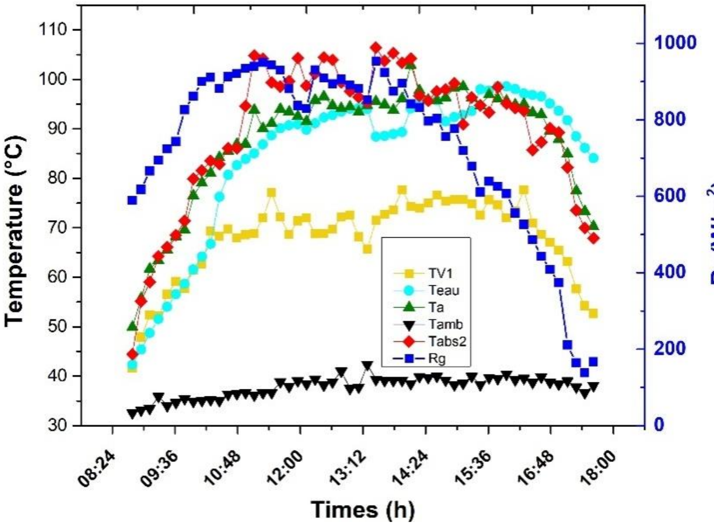

Figure 5: Time evolution of the absorber (Tabs), glazing (Tv1), internal air(Ta), water (Teau), and ambient temperatures (Tamb) and global solar irradiation (Rg)

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

3.2 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 into the chimney. Figure 6 shows the cooker with the chimney used when operating exclusively in biomass mode.

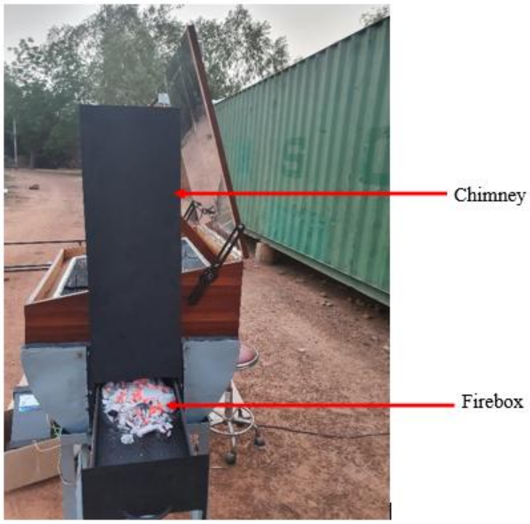

Figure 6: cooker with combustion chamber used when operating in biomass mode only.

3.2.1 No-load test

Figure 7 presents results 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.

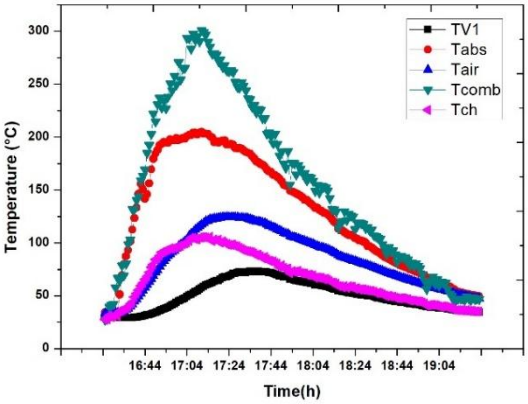

Figure 7: Time course of combustion temperature (Tcomb), absorber temperature (Tabs), glass 1 temperature (Tv1), indoor air temperature (Tair) and cooker chimney temperature in biomass mode.

3.2.2 Test with Load

Figure 8 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 minutes (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 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 other 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).

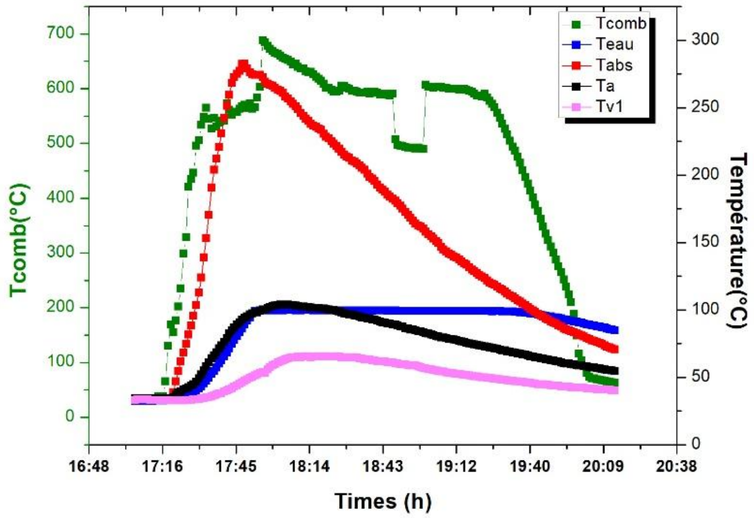

Figure 8: Temporal evolution of combustion temperature (Tcomb), absorber temperature (Tabs), glass 1 temperature (Tv1) and water temperature (Teau) of the stove in biomass mode.

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

3.3 Performance results

Table 2 presents the performance results of the different modes of tests

Tableau 2: Thermal test results

Performance parameters	**Parameter values**
$F_1(m^2C/W)$ (solar mode)	**0.1043**
F_2(SI) (solar mode)	**0.2732**
P(w) (solar mode)	**78.47**
Solar mode efficiency (%)	**29**
Biomass mode efficiency (%)	**28.4**

Table 2 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). The maximum cooking power is 78.47 W for solar cooking operations.

In solar cooking mode, the efficiency is 29 %. The efficiency of several box-type solar cookers in literature ranged from 3.05% to 35.2% (Özturk, H., 2004).

Concerning the biomass mode, the efficiency for operation was determined using equation 5. Its value is 28.4 %. Since in literature, the efficiency of traditional fireplaces is between 15 and 19 %, improved fireplaces natural convection 16 to 27 % and forced convection 30 to 35 % (R. Suresh, V. Singh, J. Malik, A. Datta, 2016).

5. 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 121.60 °C, is sufficient for cooking. The hybrid cooker gives an efficiency of 29% in solar mode and 28.4% in biomass mode, with a cooking power of 78.47 W. The results obtained are conclusive in both solar and biomass 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.

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