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A New Perspective on Experimental Analysis of Biomass Cookstove to Improve Energy Efficiency

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ABSTRACT: Improving a home's energy efficiency allows the reduction of biomass consumption and therefore human pressure on forests and improves users' health. This work aims to highlight the performance of an improved cooker based on the protocol of a water boiling test (WBT) said advanced. A suitable charcoal or firewood type is tested with wood from the province of KADIOGO, Burkina Faso. The tests took place for a month using pot number 3 with the presence and absence of its lid. The energy lost by the openings, walls, and fumes of the Cook Stove is 73.01%. The thermal performance is estimated at $\eta = 26{,}99\%$ and a maximum cooking time of 40 minutes. The improvements of this Cook Stove made it possible to achieve a gain of 10% unlike three-stone fireplaces generally have yields of about 20%. The result shows that an optimization of the cookstove that can reduce the openings is possible. The study will continue with the development of a digital method to propose a cook stove with optimal energy performance.

KEYWORDS: Wood burning; Cookstove; WBT advanced; Improved Performance.

1 INTRODUCTION

Wood biomass remains the most important source of energy production from renewable energy sources. Burkina Faso's ever-increasing population (20,505,155 in 2022)[1] and the unavailability of modern fuels are the main reasons for the increase in the use of firewood today [2]. Combustion is the main technology applied to produce heat from wood being economically feasible and controlled by households in rural areas. Also, it is a cheap and renewable source of energy but with increasing desertification, finding a solution to reduce the high demand for wood in the kitchen becomes necessary. In addition to the choice of wood with a high calorific value, the cookstove model is also an important property in the determination of energy performance. Traditionally, in Burkina Faso, the first cookstove used in the kitchen is the three-stone one. It is the simplest and cheapest cookstove to produce because it requires only three stones of the same height placed in a certain orientation [3]. The design and control of a combustion chamber reduce energy losses. Improved stoves remain much more efficient in terms of performance and safety. In recent decades, various improvements in the cookstove have been implemented through experimental studies [4]. However, there are still many parameters that need to be studied and worked on. With biomass as the main fuel, experimental studies on these stoves are needed to produce more thermally efficient and safer cookstoves. Laboratory tests have been developed to understand the gasification process in such stoves. There are many techniques used to assess range performance parameters, but the most commonly accepted is the boiling water test [5]. The Boiling Water Test (WBT) is a rough simulation of the boiling water cooking process that aims to help cookstove designers understand how energy is transferred from fuel to the pot [6]. It can be performed on almost all types of cookstoves around the world. Thus, this is the technique we have adopted to evaluate the performance of this cookstove. In addition to this protocol, we have included a procedure for measuring energy transfer from fuel combustion, ash, wall losses, and flue gas. This test determines changes in various performance parameters over time. The outputs obtained include the energy produced by the fuel, the energy consumed, and the thermal efficiency concerning time. The model of the cookstove was studied in recovered steel painted white. The originality of this study compared to the previous WBT test is the addition of the observation of the thermal compartment of the fire after the extinction of the flame. The objective of this work is to show that this type of household is more economical compared to traditional models. The document first presents the introduction, then the materials and methods, and finally the results followed by a conclusion.

2 MATERIALS AND METHODS

2.1 TEST PROTOCOL

The fuel with a mass ranging from 0.2kg to 2 kg is used to feed the cookstove. A total of 12 tests were conducted in the presence and absence of the lid. The test is first conducted at low pressure of boiling 7L of water. This amount represents 2/3 of the capacity of the pot. This phase ends when the water temperature reaches the boiling point of 99°C. Then, a high-pressure phase, with a new pot of the same volume with water is changed by keeping the cookstove warm. The water is heated to a boiling point. Finally, the test ends at the simmering phase where the water of the second boiling phase is kept on the fire for 45 minutes as planned in the study by Bagaya et al, 2021[7]. A regular check of the pot is made to avoid a descent below 6 degrees below 99°C. This last step is essential because it allows the simmering of meals during real cooking. A plus on the boiling water test was brought in this study, we extinguished the fire and left for 40 minutes to observe the behavior of the walls in the restitution of energy. The complete experiment is shown in Figure 1.

Fig. 1. Water boiling test device

The cookstove is a standard metal frame of conical shape of diameter 40 cm, of height 32cm and the wall has a thickness of 10 mm. Thermocouples in the number of 03 of type K and 03 of type J have been used for the taking of temperatures with precision of $\pm 0.5°C$ and connected to the datalogger Midi Logger LG220 whose reading tolerance is 0.05%, and accuracy$\pm 1℃$. The numerical balance has an accuracy of g. The physical model of the experiment is given by Figure 2.

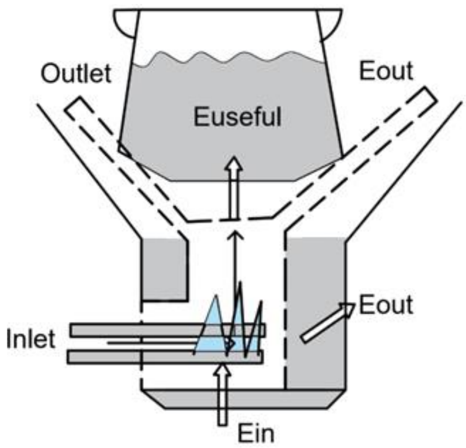

Fig. 2. Schematic of cook stove cross-section with heat transfer modes

2.2 Energy balance

The thermal balance in the cookstove is summed up in the three forms of energy. The energy dissipated in the smoke and the walls representing the upper part are named E_{out}. The thermal balance of the cookstove is determined according to the energy flows entering and leaving the cookstove. The thermal balance of the system is written in Equation 1.

$$E_{in} + E_{useful} + E_{out} = 0 \quad (1)$$

Energy supplied by fuel (kJ) E_{in} in the equation 2, is evaluated from the lower calorific value (LCV) of the wood, m_{wood} the biomass mass and m_{ash}ash mass.

$$E_{in} = (m_{wood} - m_{ash}) \text{ LCV} \quad (2)$$

Useful energy (kJ) E_{useful} in the equation 3, is all the energies served at boiling water between temperature intervals T_1, and T_2 during heating time t.

$$E_{useful} = \frac{m\,(C_p + C_{pW})(T_f - T_i) + m_{H_2Ovap}\,L_W}{t} \quad (3)$$

With m the mass of the pot loaded with water (kg), t the time (in seconds), and Lw the latent heat of vaporization ($kJ\ °C^{-1}$) and, C_P the aluminum specific heat ($kJ\ kg^{-1}°C^{-1}$) and C_{P_W} the aluminum specific heat ($kJ\ kg^{-1}°C^{-1}$). m_{H_2Ovap} represent the mass of water lost in the vaporization (kg). Thermal losses (kJ) E_{out}come down to the conduction calculated according to the Fourier law, the radiation with the Stefan-Boltzmann law, and the convection calculated by equation 4.

$$E_{out} = \frac{k\,A\,dT}{dx} + h\,A\,\Delta T + \varepsilon\,A\,\sigma\,T^4 \quad (4)$$

With $x$the cooker thickness, thermal conductivity ($Wm^{-1}K^{1}$), Aheating area (m^2), h convection coefficient ($Wm^{-2}K^{1}$), εthermal emissivity and σBoltzmann constant.

The energy efficiency (η) of the cookstove is given by the equation 5. This result defined the quotient of the energies received by the water by the energies coming from the combustion of wood.

$$\eta = 100\% \, \frac{\sum E_{useful}}{\sum E_{in}} \quad (5)$$

3 Results And Discussion

3.1 Comparison of Boiling Temperatures

Figure 3 shows the boiling water temperatures during the three WBT test phases as a function of time. In total, an average time of about 95 minutes was used for the test. Figure 3.a shows the test with a lid and Figure 3.b without a lid. It is noted that the boiling temperature of water increases rapidly in 20 minutes to reach 99°C. Such a speed provides the advantage of cooking meals faster and saving wood. For the first two phases the time to reach boiling is almost identical around 30 minutes, this explains the low inertia of the cookstove because the hot start should reach boiling faster. In the third phase, the temperature remained constant around 99°C during the 45 minutes. This is a good clue for the quivering of meals because any sudden temperature change can spoil meals. Also, the study shows that low fuel consumption is observed for the test with a lid. This good result is due to the effect of the lid reducing the losses in the pot arriving very quickly to a boil (20 minutes). Also, this good result is because the combustion chamber is close to the pot (h = 10cm) allowing a good transfer of energy to the pot.

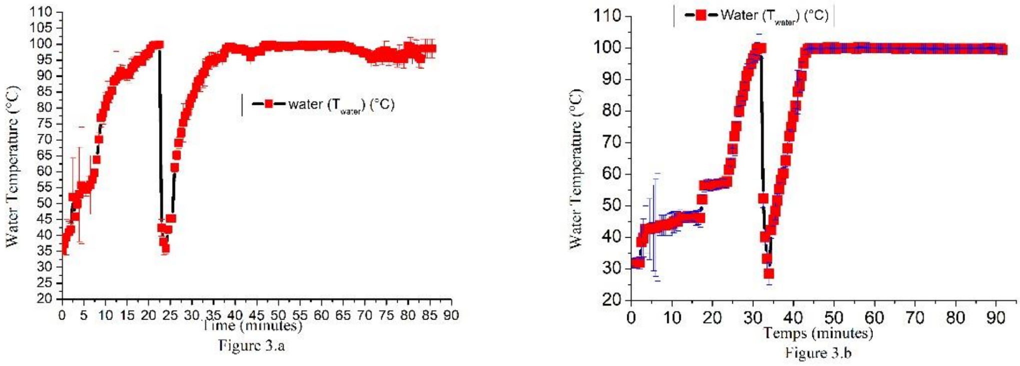

Fig. 3. Boiling temperature of water with lid (left) and without lid (right)

3.2 THERMAL INERTIA OF THE COOKER

Figure 4 shows the evolution of ambient and low temperatures of the cooker deposited on the ground as a function of time. Figure 4.a shows during heating and 4.b shows the cooling period. We notice a temperature reaching 140°C showing energy losses in this wall directly in contact with the combustion chamber. But nevertheless, this result remains acceptable compared to the temperature of the ash at T_{char} =500°C, so about 300°C is retained by this wall. Figure 4b shows a rapid drop in temperature from 140 to 40°C, indicating low inertia of the steel. Nevertheless, for 15 minutes after flame extinguishing, the temperature is still 80°C showing good model performance.

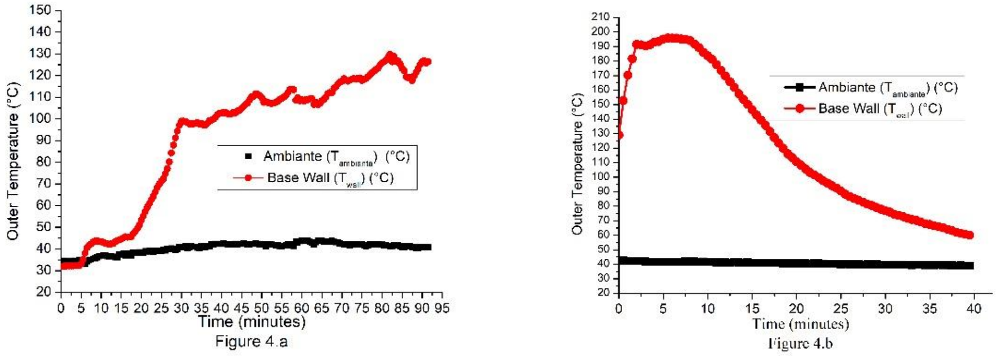

Fig. 4. Ambient and base temperatures of the cookstove during heating and cooling

3.3 HIGH TEMPERATURES REACHED

Figure 5 shows the flame and coal temperatures during the test. The maximum flame temperature is 900°C and is very close to a liquefied petroleum gas (LPG) flame[8]. This result shows that the combustion was complete and that the combustion chamber is well ventilated. This temperature allowed in 20 minutes of combustion to reach a boil. The combustion time is 100 minutes showing the energy performance of the cookstove ($\eta = 26.99\%$). Figure 5b shows the evolution of the heat in the chamber after the flame is removed. The two curves of this figure are practically identical because it is the hot ash that maintains this heat within the chamber.

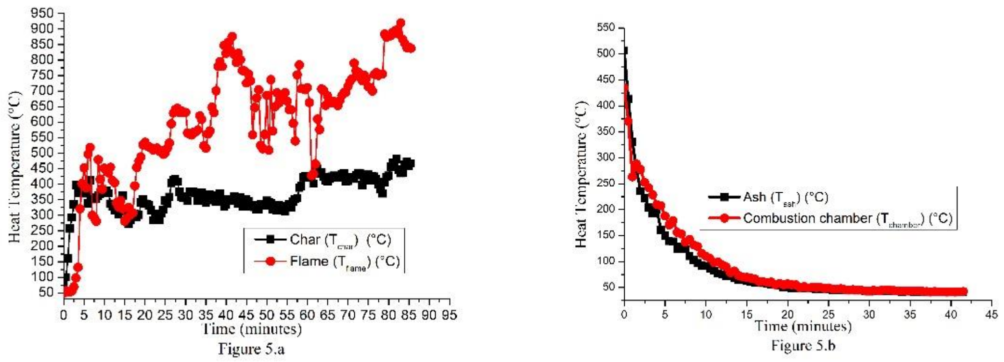

Fig. 5. Temperature trends in the combustion chamber before and after heating

3.4 TEMPERATURES OF THE VERTICAL WALLS OF THE COOKSTOVE

Figure 6 shows the temperature profile of the top wall of the cookstove reached 190°C in 5 minutes of cooking. Thereafter we observe a sinusoidal evolution ranging from 110°C to 170°C. This is due to the variation in the rate of wood combustion in the chamber. As soon as the flame dies out (Figure 6.b), the temperature of the firebox wall drops rapidly within 20 minutes to reach ambient temperature (40°C). This result shows that the inertia of the cookstove is low. Indeed, all the heat of the combustion zone passes by conduction through the wall of the cooker. The internal and external temperature of the cookstove wall is almost identical.

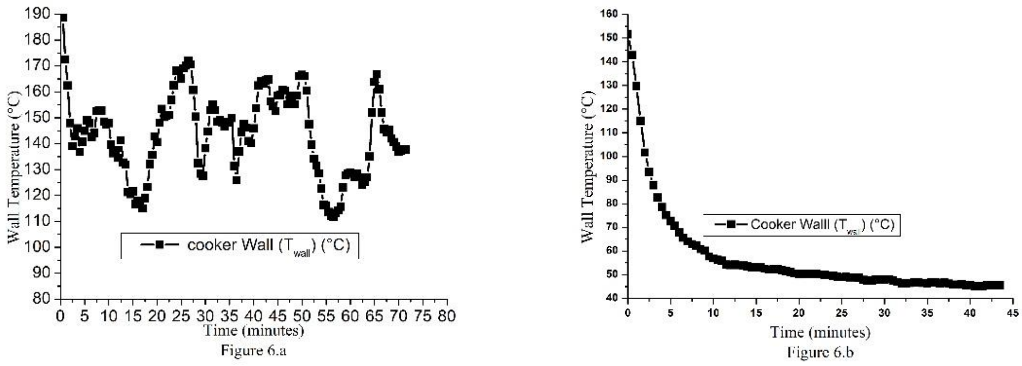

Fig. 6. Temperature evolution of the vertical wall of the cooker before and after heating

3.5 THERMAL BALANCE

Finally, the energy performance of the cookstove is presented in Table 2. During the test, the initial water temperature is 29°C and the boiling temperature is 99°C. This gives the average burner yield of 26.99% and losses of about 73%. The average partial yield of boiling is$\eta = 31.3$ %.

Table 1. Baseline energy balance result

Energy	E_{in}	E_{useful}	E_{out}
Energie (kJ)	20496	5531.8758	14964.1242
Energie (%)	100	26.99	73.01

The average boiling time is about 20 min. This result is superior to the improved yields which are around 20% [9].

4 CONCLUSIONS

The design of a prototype wood cookstove and a pot of 11 liters diameter 40cm was realized. An improved water boiling test was performed to measure overall and partial performance using wood fuel. The highest overall thermal efficiency of

26.99% while the average partial thermal efficiency is 31.3%. The study indicated that heat was concentrated inside the combustion chamber due to the shape of the combustion chamber. The implementation of a new perspective including temperature control in the WBT gave satisfactory results. The low temperatures are those of the vertical wall (150°C) and the kitchen environment (40°C). The heat flow generated indicated that the wall thickness of the cookstove can be increased as well as aeration in the chamber to achieve better performance.

COMPETING INTERESTS AND ETHICAL ISSUES

The authors declare that they have no competing interests. The different authors certify that this manuscript is the original work of the authors, and all data collected during the study are as presented in this article, and no data from the study has been or will be published separately elsewhere.

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