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(RESEARCH ARTICLE)

Experimental study of improved cookstove with primary and secondary sources

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Abstract

Improved cookcookstoves are cooking devices using biomass such as wood and charcoal. Although existing improved cookcookstoves contribute to reducing wood consumption, this consumption is still considerable, and the smoke produced is a source of many illnesses. It is therefore necessary to work on further improving these "improved cookstoves". The present work concerns the construction of an improved cookstove with primary and secondary sources. The device is essentially made from recycled materials. Boiling tests were carried out, the mass of charcoal consumed recorded and the efficiency of the cookstove calculated. The results obtained from the water boiling test experiments show that the boiling time with the secondary-source cookstove is faster than with the primary-source cookstove alone. The secondary-source cookstove has an overall thermal efficiency of 38%, while the improved single-primary-source cookstove has an overall thermal efficiency of 11%. In terms of total charcoal consumption, the primary-source cookstove consumed 1.19 kg throughout the test, while the secondary-source cookstove consumed just 0.38kg.

Keywords: Improved cookstove; Primary source; Secondary source; Water boiling, yield

1. Introduction

Biomass is the main energy supplier, accounting for the largest share of total energy consumption in rural areas of developing countries, for cooking, water heating, etc. [1]. More than 3 billion people worldwide depend on solid fuels such as firewood, charcoal or crop and food processing residues to meet their cooking energy needs. In rural areas of developing countries, traditional biomass fuels account for over 90% of household energy consumption [2] [3]. Although several countries have made considerable progress in gaining access to modern fuels and improved cooking technologies, transitions to modern energy systems remain impossible in much of the developing world. Nowhere is this more pronounced than in sub-Saharan Africa, where the absolute number of people relying on wood fuels (firewood and charcoal) to meet basic household energy needs is set to increase over the coming decades [4]. Of all biomass thermal conversion products, charcoal is the oldest, and its applications are still numerous [5].

Biomass cookcookstove design has been an active field for decades, and has led to many advances towards cleaner, more efficient cookcookstoves. Improved biomass cookcookstoves are often seen as a game-changer for cooking in developing countries. Against this backdrop, the United Nations has launched the "Sustainable Energy for All" initiative, with the ambitious goal of universal adoption of clean cookcookstoves and electricity by 2030 [6]. In sub-Saharan Africa , fuelwood consumption has doubled since 1990 [7, 8]. Charcoal is the main source of cooking energy for urban households in sub-Saharan Africa, where almost 80% of the population use it as part of their cooking energy mix [9, 10]. Burkina Faso, a Sahelian country located in West Africa, is not endowed with large forests, which are generally a source

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of wood supply. Burkina Faso's forests cover 8.6 million hectares, or 31.6% of the country's surface area. However, wood remains the primary energy source for cooking. Charcoal is the product obtained from the pyrolytic process of organic matter (mainly wood) carried out at low oxygen concentrations and low temperatures to avoid complete combustion of the biomass into ash [11, 12]. The use of wood and charcoal is increasing. This is causing an energy crisis, expressed above all in the growing scarcity of wood and charcoal as a result of environmental degradation [13, 14]. It is in this context that, in support of various reforestation operations, a number of projects and organizations have begun to popularize improved cookstoves to rationalize the use of firewood and charcoal [15]. They offer several advantages over wood, including higher calorific value, faster ignition times and ease of transport and storage [16].

In addition, the widespread use of improved cookcookstoves would reduce household consumption of wood and charcoal for cooking purposes, thus reducing greenhouse gas emissions and saving over 50% of charcoal.

Improved cookstoves can significantly reduce the environmental and health problems caused by traditional cookstoves. Improved forced-draft cookstoves show the greatest promise for reducing black carbon emissions from biomass combustion [17]. Particulate matter (PM 2.5) emissions were found to be lowest for advanced forced-draft cookstoves compared with traditional cookstoves. An experimental study was carried out to compare particulate emissions from improved and traditional biomass cookstoves, and the results indicated that CO and PM emissions decreased significantly for improved gasifier cookstoves compared with 1bree stone cookstoves [18]. Recent advances such as cookstove construction materials, combustion chamber air supply, design methodology and testing methods have been discussed in depth to improve the performance of traditional cookstoves.

For this work, we will produce an improved cookstove with primary and secondary sources. This is a cookstove model consisting of an outer cylinder with primary (door) and secondary (holes) air inlets, and an inner cylinder with a hot secondary air inlet to the combustion chamber. The overall aim of this study is to contribute to fuel savings in household use. To achieve this objective, we will build the improved cookstove and carry out an experimental study based on a water boiling test.

2. Materials and method

2.1. Materials and tools required for cookstove manufacture

2.1.1. Tools required

The tools required are of several types, including the following:

Templates - Scissors, hammer, chisel, pliers, scribing nail/attachment point, 2mm and 10mm punch, compass (0.5cm, 1.5cm, 2cm) and paintbrush.

2.1.2. Cookstove construction materials

The materials used to build the cookstove are: sheet metal (12mm), a nail and black pain

2.1.3. Steps in the construction of an improved cookstove with primary and secondary sources

- **The outer cylinder of the cookstove** is round, with a diameter of 19.9 cm, and is bent 0.5 cm inwards around the door opening. It is also bent at the top by 0.5 cm at 45° outwards, allowing primary air to enter through the door and secondary air through the circular holes drilled in the bottom. The holes are spaced 0.5 cm apart.
- **The inner cylinder** is round, 17cm in diameter, bent outwards at 0.5cm 45°. The sides of the door are also bent outwards by 1.2 cm at 90°. Holes are also drilled to allow hot secondary air to enter.
- **The combustion chamber** is the vital part of the cookstove. Its role is to mix the compressed air with the fuel and, through combustion, transform its chemical energy into thermal energy.
- **The bottom** is folded 0.5 cm inwards, and the holes are drilled 1 cm apart. In this way, the base is held in place by supports which are formed with clamps.
- **The cookstove base**: First, note that the cookstove base is characterized by two circles, 24 cm and 22 cm in diameter on the upper plate, which is folded 0.5 cm flat on the outside. Next, the base is pierced with eight openings, to enable the outer and inner cylinders to be attached, and finally the base is folded 0.5 cm from the lower plate.
- **The conical support** is marked out using the template. It is made up of the pot supports formed by a tube and the 0.5 cm folded arms formed into a semi-lunar shape.

- **The door**: The cookstove consists of a door, a handle and a latch, the edges of which are folded inwards by 0.5 cm. A hole is drilled in the door, and a nail is used to fix the hinge. The door, hinge and handle are assembled as follows.

Figures 1 to 6 show the different parts of the cookstove

Figure 1 Outer cylinder

Figure 2 Inner cylinder

Figure 3 Combustion chamber

Figure 4 Cookstove base

Figure 5 Conical support

Figure 6 Door

Figure 7 shows some assembly steps for the improved cookstove

Figure 7 Assembling the various parts of the primary- and secondary-source cookstove

The assembly of all these components forms the improved cookstove shown in figure 8.

Figure 8 Finished cookstove (primary and secondary source cookstove)

Figure 9 Primary-source cookstove

The primary-source cookstove consists mainly of a single air intake through the door. The other parts are identical to those of the secondary-source cookstove.

2.1.4. Cookstove operating principle

The secondary-source cookstove uses twice the power of charcoal: radiant heat and the combustion of unused gases. In fact, the improved cookstove operates with a primary source characterized by an air intake through the cookstove door and another source based on the gasifier principle. A secondary air supply through the holes in the outer cylinder then burns the unused gases.

Complete charcoal combustion via the secondary air supply considerably reduces emissions of gases harmful to health and the environment.

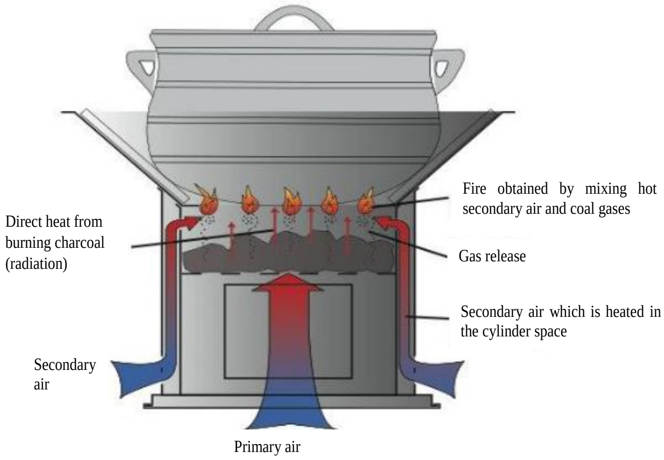

Figure 10 : Principle of operation

Figure 11: Hearth filled with coal

How to use the cookstove.

This type of improved cookstove is very easy to use, the method of operation is as follows:

- Fill charcoal to the top of the combustion chamber.
- Light the charcoal as usual
- Don't put the pot in the fire until there's a good ember.

- Once the meal has boiled, close the door to save charcoal
- Use a lid

Cookstove maintenance

It's important to keep the cookstove air flowing properly. Therefore, remove ashes after cooking, clean the combustion chamber and replace the bottom if broken..

2.2. Experimental protocol

The boil-water test consists of three phases, immediately following each other.

In the first phase, called cold start, the test begins when the cookstove is at room temperature. Pre-weighed charcoal is used to bring a measured quantity of water to the boil. The pot of boiling water is then replaced by another pot containing cold water to begin the second phase of the test.

The second phase is called the hot start. It immediately follows the first phase while the cookstove is still hot. This phase helps to determine the difference in performance of the cookstove when it is cold and when it is hot.

The third phase immediately follows the second. It is called the low-power phase, the previous ones being high-power phases. Here the phase involves determining the amount of charcoal required to simmer water just below boiling point for 45 minutes. This step simulates long cooking times. The combination of these phases results in aspects of performance on both the high and low wattage cookstove, which is associated with the cookstove's ability to retain heat.

2.2.1. Steps to follow before starting the test

Starting the test requires the following important steps:

- Be sheltered from the wind so as not to distort measurements (uncontrollable fluctuation in airflow rates).
- Be sheltered from the sun in order to have a significant measured ambient temperature.
- Be sufficiently insulated to avoid the passage of people who could create draughts or disturb the testers.
- Carry out the test in a place allowing easy evacuation of fumes, to avoid inhalation of the latter.
- Weigh the empty pot: this mass will be noted (MV).
- Fill the pot with water to 2/3 of its capacity.
- Replace the lid and thermometer
- Weigh the full pot, still with lid and thermometer: note (M0) this mass
- Clean the cookstove perfectly, then weigh it empty and note (FV) this mass
- Fill the cookstove to the brim with coal
- Light the fire with twigs or a tablespoon of kerosene (10 to 15ml) without putting the pot down
- Five minutes after lighting, weigh the full cookstove and note (F0) this mass
- Place the pot full of water, with lid and thermometer in place, and start the timer.
- If there is a door closing flap, it must remain open
- Read the temperature every five minutes, without moving the pot or the cookstove
- When the water starts to boil, note the time (TE)
- Weigh the complete pot (water, lid and thermometer included) and note the time (M1)
- Weigh the cookstove containing the full remaining coal (without the pot) and note (F1)
- Place the pot back on the cookstove and close the shutter, if fitted, for 60 minutes.
- Make sure that the water temperature does not fall below the boiling temperature: if this happens, it is no longer valid
- 60 minutes after boiling begins, weigh the complete pot and record (M2)
- Weigh the cookstove full of charcoal and remaining embers and note (F2)

2.2.2. Equipment required for testing

A mechanical balance: This is used to measure the masses of the elements to be used.

OMEGA HH12B thermometer: used to measure water temperature.

Figures 12 to 14 show the equipment used and the measurements made.

Figure 12 Scale used

Figure 13 Thermometer

a b c d

Figure 14 Measurements: a) weighing charcoal b) weighing empty pot c) weighing cookstove d) measuring water temperature

To report on the behavior and performance of the cookstove, the following results should be expressed:

- TE: Time required to reach boiling point (in mn)
- TES: Specific boiling time, i.e. time required to bring one liter of water from 0 to 100°C (in min/l)
- ɳ1: Thermal efficiency of the cookstove for the first phase (high-power phase ending with boiling), i.e. the ratio of the energy recovered by the contents of the kettle to the energy produced by combustion during the first phase (%).
- CS1: Specific consumption of the first phase, i.e. the quantity of coal needed to bring one liter of water from 0 to 100°C (kg/l).
- P1: Power during the first phase, i.e. the amount of energy produced during the first phase per unit of time (kW).
- ɳt: Total thermal efficiency, i.e. the ratio of the energy recovered by the contents of the kettle to the energy produced by combustion during the entire test (%).
- CS2: Specific consumption of the second phase, i.e. the quantity of coal required to evaporate one liter of water during the second phase (kg/l).
- P2: Power during the second phase, i.e. the amount of energy produced during the second phase per unit of time (kW).

- CT: Total coal consumption during test (kg)
- MEV: Mass of water evaporated during test (kg)

2.3. Calculation method

The tests were carried out on two cookstoves. One was a primary-source-only cookstove, and the other a primary- and secondary-source cookstove. This makes it possible to determine the performance of our cookstove, and also to compare its performance with that of the primary-source-only cookstove currently in use.

2.3.1. First phase calculation method

Correction coefficient for initial water temperature (K):

The initial water temperature is reduced to 0°C by the following correction coefficient :

$$K = \frac{100-T_0}{100} \text{ .... (1)}$$

With T_0: initial water temperature, in °C

Other coefficients

- Co = 4..18 kJ /kg (heat capacity of water)
- Li = 2260 kJ/kg (latent heat of vaporization of water)
- PCI= 29000 kJ/kg (lower calorific value of coal)

Specific boiling time TES (min/l)

The specific boiling time TES [19] is given by equation 2 :

$$TES = \frac{TE}{M_1-M_V} \times \frac{100}{100-T_0} \text{ .... (2)}$$

Yield (in %)

$$\eta = \left[\frac{4{,}18(M_1-M_V)(100-T_0)+2260(M_0-M_1)}{29000(F_0-F_1)}\right] \times 100 \text{ .... (3)}$$

First-phase power P_1(in kW)

$$P_1 = \frac{29000(F_0-F_1)}{TE(mn)\times 60} \text{ .... (4)}$$

Specific consumption for first phase CS_1 (in kg/l) :

$$CS_1 = \frac{(F_0-F_1)}{(M_1-M_V)} \times \frac{100}{(100-T_0)} \text{ .... (5)}$$

2.3.2. Second stage calculation method

Specific consumption of second phase CS_2 (in kg/l) :

$$CS_2 = \frac{F_1-F_2}{M_1-M_2} \text{ .... (6)}$$

Second-phase power P_2(en kW)

$$P_2 = \frac{29000(F_1-F_2)}{30\times 60} \text{ .... (7)}$$

2.3.3. Calculation method for total boiling water test

Total test yield :

$$\eta_t = \left[\frac{4{,}18(M_1-M_V)(100-T_0)+2260(M_0-M_2)}{29000(F_0-F_2)}\right] \times 100 \text{ ....(8)}$$

Total coal consumption (in kg)

$$CT = FO - F2 \text{ ....(9)}$$

Evaporated water masse

$$MEV = M_0 - M_2 \text{ .... (10)}$$

3. Results and discussion

Table 1 shows the test results for the two cookstoves. The values are then used to determine the performance of the cookstoves.

Table 1 Data collection during TEE

Data / Type of cookstove	M_V	M_0	M_1	M_2	F_0	F_1	F_2	F_V	T_0
Secondary source	1.20	2.73	1.95	0.95	4.46	4.13	4.08	3.5	32.1
Source primaire	1.56	2.87	1.92	1.23	4.31	3.95	3.12	2.83	32.1

The performance results for the primary-source cookstove and the secondary-source cookstove are shown in the calculations below:

3.1. Specific boiling time TES (mn/l)

For the secondary-source cookstove

$$TES = 35{,}34\ mn/l$$

For primary-source cookstoves

$$TES = 98{,}17 \text{ mn/l}$$

3.2. Yield (in %)

For secondary-source cookstoves

$$\eta = 20\%$$

For primary-source cookstoves

$$\eta = 21\%$$

3.3. Power of the first phase P_1(in kW)

For the secondary source cookstove

$$P_1 = 8{,}86 kW$$

For the primary source cookstove

$$P_1 = 6{,}64 kW$$

3.4. Specific consumption of the first phase CS_1 (in kg/l)

For the secondary source cookstove

$$CS_1 = 0{,}64 kg/l$$

For the primary source cookstove

$$CS_1 = 1{,}35 kg/l$$

3.5. Specific consumption of the second phase CS_2 (in kg/l)

For the secondary source cookstove

$$Cs_2 = 0{,}05 kg/l$$

For the primary source cookstove

$$CS_2 = 1{,}20 Kg/l$$

3.6. Second phase power P_2(in kW)

For the secondary source cookstove

$$P_2 = 0{,}80 kw$$

For the primary source cookstove

$$P_2 = 13{,}37 kw$$

3.7. Total yield of the test :

For the secondary source cookstove

$$\eta t = 38\%$$

For the primary source cookstove

$$\eta t = 11{,}03\%$$

3.8. Total coal consumption (in kg)

For the secondary source cookstove

$$CT = 0{,}38 kg$$

For the primary source cookstove

$$CT = 1{,}19 kg$$

3.9. Evaporated water mass

For the secondary source cookstove

$$MEV = 1{,}78 L$$

For the primary source cookstove

$$MEV = 1{,}64 L$$

The summary results of the various calculations are shown in Table 2 below :

Table 2 Summary of results

Data / Type of cookstove	TE	TES	η_1	CS_1	P_1	η_t	CS_2	P_2	CT	MEV
Secondary source	24	98.17	21	1.35	6.64	11	1.20	13.37	1.19	1.64
Source primaire	18	35.34	20	0.64	8.86	38	0.05	0.80	0.38	1.78

Total charcoal consumption was 1.19 kg for the primary-source improved cookstove and 0.38 kg for the secondary-source improved cookstove. This shows that the primary-source-only cookstove consumed more than three times as much charcoal as the secondary-source cookstove.

The improved secondary-source cookstove reached a boiling point of 18 minutes, while the single-primary-source cookstove reached a boiling point of 24 minutes. If we were to limit ourselves to this observation, we'd say that the secondary-source cookstove is faster and therefore more efficient than the single-source cookstove. In the gasifier principle, the fuel is first burned in a primary combustion zone, where it is transformed into gases. These gases are then burned in a secondary combustion zone, where they are mixed with air to produce a cleaner, faster flame. As a result, we obtained a total efficiency of 38% for the secondary-source cookstove, compared with 11% for the primary-source cookstove. In view of these results, we can see that the improved secondary-source cookstove performs better than the improved primary-source cookstove alone. Figure 15 shows water temperature trends in the two cookstoves during the first test phase.

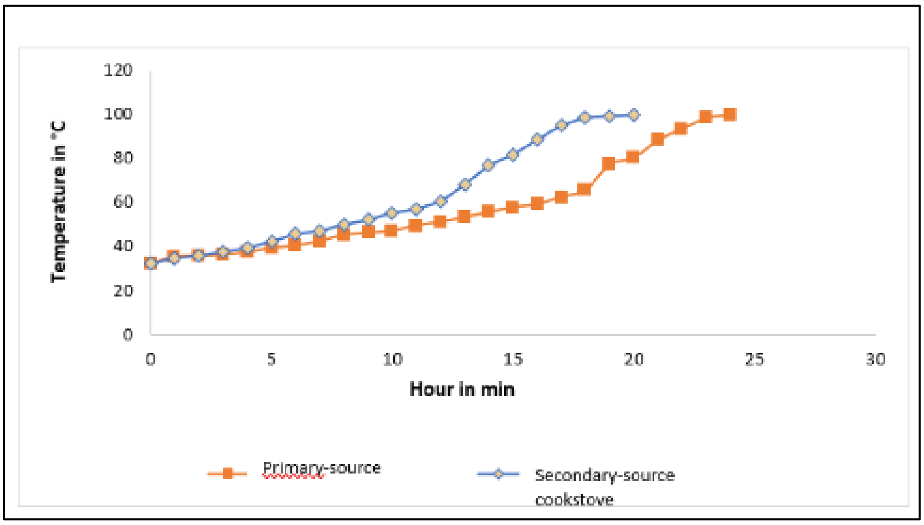

Figure 15 Water temperature curves for the two improved cookstoves as a function of time

These curves show that the water temperature in the secondary-source cookstove rises faster than in the primary-source cookstove. With the improved secondary-source cookstove, the water reaches boiling point after 18 minutes. With the primary-source-only cookstove, on the other hand, the water boils after around 24 minutes. This difference in time to boiling reflects the improved heat transfer of the secondary-source cookstove. This time saving comes at the cost of fuel savings..

4. Conclusion

Our work involved the construction and experimental study of improved primary and secondary source cookstoves. The cookstoves were designed after determining the correct dimensions. We then carried out an experimental and comparative study of the two cookstoves. This study mainly concerned the water boiling test, which enabled us to determine the performance of these cookstoves. The improved primary- and secondary-source cookcookstove tested meets a key concern: fuel economy and rapid boiling time. It has a total thermal efficiency of 38% and a boiling time of 18 minutes, while that of the single primary source has a thermal efficiency of 11% and a boiling time of 24 minutes. This cookstove therefore meets our expectations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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