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Enhanced Carbon Neutral and Performance Characteristics Cookstove for Energy Sustainability

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Samson Kolawole Fasogbon
ORCID: https://orcid.org/0000-0001-8023-9369
University of Ibadan, Ibadan, Oyo State, Nigeria
E-mail: sk.fasogbon@ui.edu.ng
Emmanuel Segun Durowoju
ORCID: https://orcid.org/0009-0003-7892-7121
Texas A&M University, Kingsville, Texas, USA
E-mail: durowojues@gmail.com
Theophilus Chibuzo Uzoh
ORCID: https://orcid.org/0009-0001-4363-0171
Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria
E-mail: uzohtheophilus@yahoo.com
Kubiat Edeheudim George
ORCID: https://orcid.org/0000-0002-5906-3175
University of Louisiana, Lafayette, Louisiana, USA
E-mail: kubi4all@gmail.com
Mark Onons Ikhifa
ORCID: https://orcid.org/0009-0001-6762-4390
University of Louisiana, Lafayette, Louisiana, USA
E-mail: markoatdetop@yahoo.com
Timilehin Daniel Adegoke
ORCID: https://orcid.org/0009-0004-5300-0925
University of Ibadan, Ibadan, Oyo state, Nigeria
E-mail: timilehindaniel8888@gmail.com
Ibrahim Ademola Fetuga
ORCID: http://orcid.org/0000-0002-1943-4234
University of Lagos, Akoka, Lagos, Nigeria
E-mail: fetugaebraheem@gmail.com

Abstract

Open fire cooking, which consists of either three stones arrangement in a triangular shape or iron three legs fabricated stove (Adogan), is a common way of cooking in developing and underdeveloped countries. This method of cooking is simple, but comes with its inherent problems that threaten energy sustainability concept; in a way of its harmful gases emissions, high cost; as occasioned by thermal inefficiency which also culminates in to high depletion rate; and ultimately deforestation. These energy sustainability factors and time wastages on wood fetching; had led significant number of researchers to investigate improvement process of the traditional cookstove; and have therefore developed some enhanced cookstoves for use. The article is aimed at designing an enhanced carbon neutral and performance characteristics cookstove for energy sustainability. Analytical basis, experimental studies and performance testing were conducted on existing improved traditional stove; with three burners of orifice sizes 0.8 *cm*, 1.0 *cm*, and 1.2 *cm*. The model with burner orifice size 1.2*cm* presented highest thermal efficiency, lowest specific fuel consumption and lowest CO ppm. The study arrived that for any enhanced traditional cookstove to give optimal energy sustainability model, burner orifice size of 1.2 *cm* should be employed.

Keywords: Cookstove. Biomass fuel. Orifice sizes. Burn rate. Flue gas emission, Specific heat consumption

1. Introduction

Burning biomass fuel in conventional stoves is linked to a slew of health problems among the estimated 2.5 billion people who lack access to modern fuel Muchiri (2008). Burning wood, charcoal, animal dung, or crop residue heats an upgraded conventional kitchen stove for cooking. In developing and underdeveloped countries, cook stoves are the most popular method for cooking and heating food. One of the main aims of the suitable and sustainable technology revolution has been to develop an inexpensive stove that is more effective than the widely used three-stone fire pit.

Current research on improved cook-stoves reveals that stoves prove to be an effective fuel saving method of cooking for household dependent on fuel-wood; the challenge exists in encouraging individuals to use the improved cook-stoves. Improved cook-stoves are a promising measure for sustainable and efficient use of fuel-wood (Honkalaskar *et al*., 2013; Vahlne and Ahlgren, 2014; Mehetre *et al*., 2017; Mwaura, 2020; Onah *et al*., 2021). Homi Katrak (2009) indicated that enhanced stoves could lead to reductions in both the consumption of solid fuels and the time required for cooking. This improvement could result in decreased spending on fuel, contributing to poverty alleviation. Additionally, it would benefit women by reducing the time and effort needed to gather fuel, and it would also lower smoke emissions. Consequently, this reduction in emissions would minimize the health hazards encountered by children and women in these households. Sinton *et al*. (1995) highlighted that the variation in emissions is influenced by the specific types of stoves and fuels employed. By comparing emission factors across a range of stove and fuel mixtures, it's possible to establish a scale for measuring pollutant emissions, thereby providing a benchmark for evaluating efficiency.

Adams *et al*. (2023) examined the factors and challenges influencing the adoption of improved cook stoves (ICS) in Ghana, a developing country facing energy and environmental issues. They used a mixed-methods approach, combining logistic regression and non-parametric models to analyze data from 194 purposively selected households. They find that household size, education, availability, and frequency of use are significant determinants of ICS adoption, while affordability, awareness, accessibility, and quality are the main barriers. Rasoulkhani *et al*. (2018) compared the thermal performance of improved biomass stove with the traditional cook stove (TCS) at time to boil ranging from 12 to 20 min. They indicated that the thermal efficiency was improved by 35% in ICS as compared to TCS while the total and specific fuel consumption were decreased by 67% and 73%, respectively as compared to TCS. Matavel *et al*. (2023) explored the cost-effectiveness of different dissemination techniques for promoting the adoption of improved cookstoves (ICS) in rural Mozambique. They conducted an experiment with 510 households, randomly assigned to receive individual video training, on-site group training, or a combination of both. They found that individual video training had the highest adoption rate (53%) and the lowest training cost, while on-site group training had the lowest adoption rate (21%) and the highest training cost. Gutierrez *et al*. (2023) examined the design practices of a government program that promotes the usage of improved cookstoves (ICS) in rural areas of Colombia. They found that the program's design was not user-centered, resulting in low adoption rates and dissatisfaction among the households. They further suggested that using a more human-centered design approach could complement more traditional design methods and enhance the effectiveness and sustainability of ICS programs.

Gill-Wiehl *et al*. (2023) conducted household energy surveys with main cooks across four villages and found that liquefied petroleum gas (LPG) was the most preferred clean fuel, followed by electric stoves. They also assessed the affordability and availability of LPG and electric stoves in the local market and found that LPG was more feasible than electric stoves. Wathore *et al*. (2023) developed two models of biomass mud cookstoves (BMC), Pavak 1 and Pavak 2, using multi-parameter optimization based on laboratory testing. They compared the MBCs with traditional stoves (TS) using the ISO 19869:2019 field testing protocol and carbon balance method. The results show that the MBCs reduced PM2.5 and CO emissions by 37–56% and 0.85–15%, respectively, compared to TS. Mehetre *et al*. (2016) evaluated the performance of an improved cook stove that uses carbonized cashew nut shell as a fuel. They tested the cook stove for its fuel consumption, thermal efficiency, and emission characteristics. They reported that the cook stove has a thermal efficiency of 31.5%, a fuel consumption of 0.25 *kg/h*, and a low emission of carbon monoxide and particulate matter. Chagunda *et al*. (2017) assessed the performance of an improved cook stove (Esperanza) that uses wood as a fuel in a rural community of Malawi. They compared the cook stove with the traditional three-stone stove in terms of fuel consumption, wood savings, and indoor air pollution and the results found that the improved cook stove reduces the fuel consumption by 50%, the wood savings by 60%, and the indoor air pollution by 80%. Sonarkar and Chaurasia (2019) compared the thermal performance of three improved cook stoves using different types of biomass fuels. The results found that the cook stove using wood pellets has the highest thermal efficiency and the lowest emission factors, while the cook stove using coconut shell has the lowest thermal efficiency and the highest emission factors. Dutta *et al*. (2023) investigated the performance of an efficient biomass fired cook stove as a standby unit for community They fabricated four-burner cook stove that uses Delonix regia (Gulmohar) as a fuel. Their results claimed that the cook stove has a maximum thermal efficiency of 40%, a firepower of 86.54 *kW*, and a specific wood consumption of 0.20 *kg/kg* of water boiled.

Rural residents primarily rely on wood or biomass to satisfy their cooking requirements, prompting the launch of a program to introduce improved cooking stoves. These stoves are designed to decrease indoor air pollution and enhance energy efficiency. The adoption of more efficient cooking technologies plays an important role in alleviating the fuelwood shortage in certain Nigerian regions lacking electricity. In this study, the effect of varying the orifice sizes of the burners used in the improved traditional stove with respect to the thermal efficiency, cooking time, burn rate, and specific fuel consumption as well as cooking power was investigated. Also, emissions of gases produced by different orifice sizes of the burner were determined and the results obtained were compared.

2. Materials and Methods

2.1 Fabrication of the existing improved traditional stove and burners with different orifice sizes

The existing improved traditional stove and three burners with different orifice sizes were fabricated, the orifice sizes are 0.8 *cm*, 1.0 *cm*, and 1.2 *cm* (see Figure 1). The materials considered for the fabrication of the burners and the existing improved traditional stoves are: (a) For the outer chamber, galvanized iron sheet gauge 28 was used. (b) For the inner chamber, galvanized iron sheet gauge 26 was used. (c) For the stands (legs) and pot holder, scrap metal with poor heat conductivity was used (see Figure 1).

Figure 1 - The redesigned stove and the burner

2.2 Design Parameter

The following parameters are critical to the performance of the stove and will be employed in the design of the improved traditional stove: (i) Air flow to combustion chamber - larger amount of airflow leads to faster rate of cooking. (ii) Diameter of fuel canister - larger diameter leads to faster rate of cooking. (iii) Volume of fuel canister – a larger volume will lead to a longer cooking period. (iv) Overall height of stove – the taller the stove, the more effective is its natural draft, and also ensures that the stove burns clean. (v) Enhance the heat transfer to the pot by ensuring gaps are of the appropriate size. The most effective method for directing heat into pots involves utilizing small channels. These channels or gaps force the hot flue gases from the fire through them, facilitating improved heat transfer to the pot and thereby increasing the stove's efficiency.

2.3 Varying of burners orifice

From the existing stove to be modified, the detailed dimensions of the holes are shown in the Figure 2. The orifices diameter considered are 0.8 *cm*, 1.0 *cm*, and 1.2 *cm* while the spacing for both vertical and horizontal spacing is of 0.5 inches.

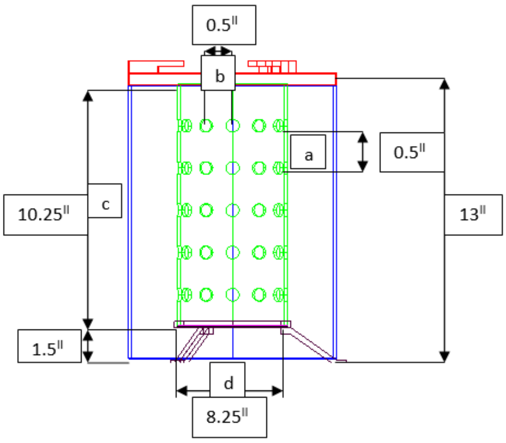

Figure 2 - Dimensions of stove: a - orifice spacing (vertical); b - orifice spacing (horizontal); c - diameter of the burner; d - height of the burner

2.4 Instrumentation

The apparatus used in this experiment include flue gas analyzer, stop watch, mechanical weighing scale and thermocouple.

Flue gas analyzer: This is a portable electronic device that is used for emission testing, to measure the source air quality from the improved traditional stove, the temperature and to determine the stove efficiency. A flue gas analyzer measures and displays the products of combustion from the exhaust of the stove. Its probe was placed in the chimney or exhaust to see what levels of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and flue gas temperature are present.

Stop watch: This device is a portable timekeeper crafted to track the duration from a specific start point to the moment it is turned off. It is intended for managing the activation and deactivation timing of a specific experiment or a series of experiments.

Mechanical weighing scale: This is used for the measurement of the various quantities of the different biomass fuels.

Thermocouple: A device equipped with a marked glass tube and a bulb filled with mercury or alcohol, which ascends within the tube as the temperature goes up, will be utilized to gauge the water's temperature.

Biomass Fuel: The biomass fuels to be burnt in the three stoves are coconut shell, palm kernel sludge, palm kernel fiber and palm kernel shell. The biomass fuel listed above were collected at Ajebandele village in Ile-Ife, Osun State and a fixed weighted sample of these biomass fuels were taken to ensure a uniform representation, and then burnt in each of these stoves. The palm kernel, sludge, shell and coconut shell were used in the state (dried) they were purchased.

Stove Testing: Stove testing involves the methodical assessment of the strengths and weaknesses of a specific stove design. The main goal is to pinpoint the most efficient and preferred stove model and to analyze the emission profile of the stove when utilizing burners of varying orifice dimensions. Such an evaluation process is essential for quality assurance and could result in significant design improvements. Palm kernel fiber served as the biomass fuel used in the stove.

Water boiling test: To measure how much palm kernel fiber is used to boil water under fixed conditions. The tests were performed both at full heat (i.e. when it boils) and the results were recorded.

Burn rate: Burn rate refers to the amount of biomass consumed over time when exposed to air. Experiments to measure the burn rate were conducted on four experimental stoves. Each stove was loaded with the specified fuel (biomass), and measurements were taken for the initial and final weight of the fuel at the beginning and end of the experiment, respectively, along with the duration of combustion. These tests were performed three times for each stove to ensure accuracy, and an average burn rate for each stove was then determined based on these trials.

Flue gas analyzer test: To determine the emission characteristics of each stove. To do this, a chimney was placed over the improved traditional stove while the flue gas analyzer probe was placed at the tip of the source from which the gases are coming out (to measure from source emission).

2.5 Analytical Basis

Weight of biomass fuel consumed

$$W_d = W_b - W_c \qquad (1)$$

where W_b is weight of biomass fuel and W_c is weight of biomass at the end of boiling

Water vaporized

$$W_v = W_a - W_p \qquad (2)$$

where, W_a is weight of pot with water and W_p is weight of pot with water after boiling

Specific fuel consumption

$$S_c = \frac{W_d}{W_w} \qquad (3)$$

where W_w = weight of water in the pot

Test duration

$$t = t_2 - t_1 \qquad (4)$$

where t_1= initial time measurement and t_2 = final time measurement at the end of boiling

Burning Rate

$$B.R = \frac{W_d}{t} \qquad (5)$$

Where t time measurement

Power Output

$$P = \frac{W_d \, x \, E_f}{t} \qquad (6)$$

where E_f is Calorific value of the biomass fuel

Thermal Efficiency $\eta = \frac{power\ input}{power\ output}$ (7)

Adjusting Equation 5 for moisture content of the fuel, it gives Equation 8;

$$R(kghr^{-1}) = \frac{100(W_i - W_f)}{(100+M)t} \tag{8}$$

Where:
W_i = Original fuel weight at start of test, kg;
W_f = End of test fuel final weight, kg;
M = Fuel humidity quality, %;
t = Complete fuel consumption time, s.
Substituting details for Equation 7, the stove's thermal efficiency was calculated using Equation 9.

$$\eta th = \frac{W_{wi} C(T_f - T_i) + (W_{wi} - W_{wf})}{R\ x\ t\ x\ Q_{net}} x\ 100\% \tag{9}$$

Where:
W_{wi} = initial weight of water in the pot, kg;
W_{wf} = final weight of water in the pot, kg;
T_i = final temperature of water, ^oC;
T_f = initial temperature of water, ^oC;
C = specific heat capacity of water, $kJkg^{-1}K^{-1}$;
L = latent heat of vaporization of water at 100^oC, $kJkg^{-1}$.
Substituting details for Equation 3, the Specific fuel consumption (SFC) was calculated using Equation 10;

$$SFC = \frac{W(1-M) - 1.5W_f}{m_{pf} - m_p} \quad 10)$$

Where:
W = mass of fuel ($Wi - W_f$), kg;
M = moisture content of fuel, %;
M_{pf} = mass of the pot with cooked food, kg;
M_p = mass of the pot, kg.

3. Results and Discussion

3.1 Water temperature versus time

The test was conducted to compare the boiling times of different burners with varying orifice sizes (0.8 *cm*, 1 *cm* and 1.2 *cm*) and a traditional stove (Adugan). As shown in Figure 3, the results of the test showed that the burner with an orifice size of 0.8 *cm* was able to boil 1.6 *kg* of water from cold start for 10.30*mins*, the burner with an orifice size of 1.0 *cm* boiled the same amount of water for 8.30*mins*, the burner with an orifice size of 1.2 *cm* boiled the same amount of water for 6.41mins, and the traditional stove (Adugan) boiled the same amount of water for 4.52*mins*. The results also indicate that the boiling time decreased as the orifice size increased. This is because the burner with the smallest orifice size produces a smaller flame, which concentrates the heat on a smaller area of the pot and reduces heat loss to the surroundings. As the orifice size increases, the flame becomes larger, which spreads the heat over a larger area of the pot and increases heat loss to the surroundings. This results in a decrease in the efficiency of the burner and an increase in the boiling time.

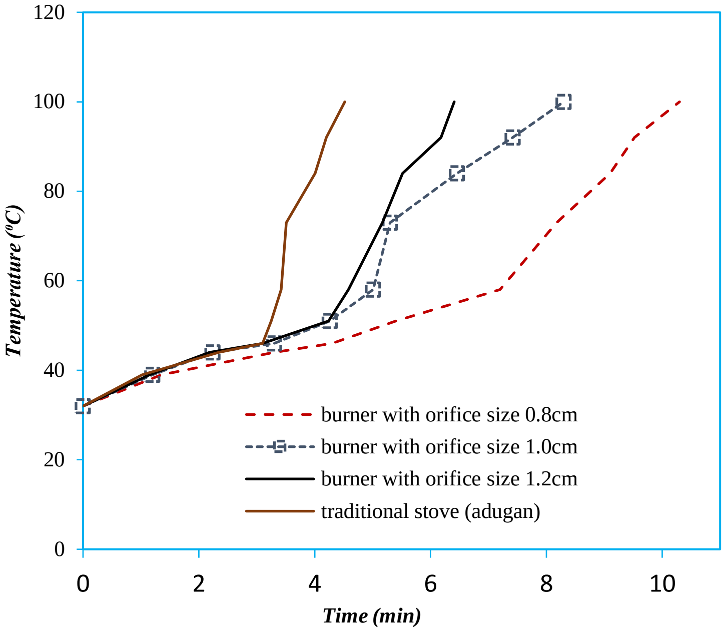

Figure 3 - Comparison of temperature profile for burner at different orifice sizes

3.2 Specific fuel consumption

As shown in Figure 4(a), the traditional stove, colloquially referred to as "Adugan," exhibits the highest specific fuel consumption at 0.63 *kg* of consumed fuel per kilogram of evaporated water. This heightened consumption can be attributed to the stove's inherently large surface area, which necessitates a greater amount of fuel to achieve the desired water evaporation.

The burner equipped with an orifice size of 0.8 *cm* demonstrates a lower consumption rate, recording 0.44 *kg* of consumed fuel per kilogram of evaporated water. This result can be rationalized by considering the optimized efficiency achieved through the 0.8 *cm* orifice, allowing for a more controlled and efficient combustion process.

The burner featuring an orifice size of 1.0 *cm* showcases a further reduction in specific fuel consumption, registering at 0.38*kg* of consumed fuel per kilogram of evaporated water. This improvement can be attributed to the calibrated size of the orifice, which strikes a balance between promoting sufficient combustion and minimizing excess fuel consumption.

The burner with the largest orifice size in the study, measuring 1.2 *cm*, exhibits the lowest specific fuel consumption at 0.31*kg* of consumed fuel per kilogram of evaporated water. The superior efficiency observed in this configuration is a direct consequence of the larger orifice facilitating enhanced airflow and combustion, resulting in a more effective utilization of the fuel for the water evaporation process.

3.3 Cooking power

Fig. 4(b) shows the cooking power comparison of the stove using the three burners, traditional stove and it can be seen that the traditional stove (Adugan) has the highest cooking power of 4.34 *kW* while in the burner with orifice size of 0.8 *cm*, 1.0 *cm* and 1.2 *cm* has cooking power of 1.33 *kW*, 1.41 *kW* and 1.53 *kW*, respectively. The cooking power increases with the orifice size. This is due to amount of specific fuel consumption.

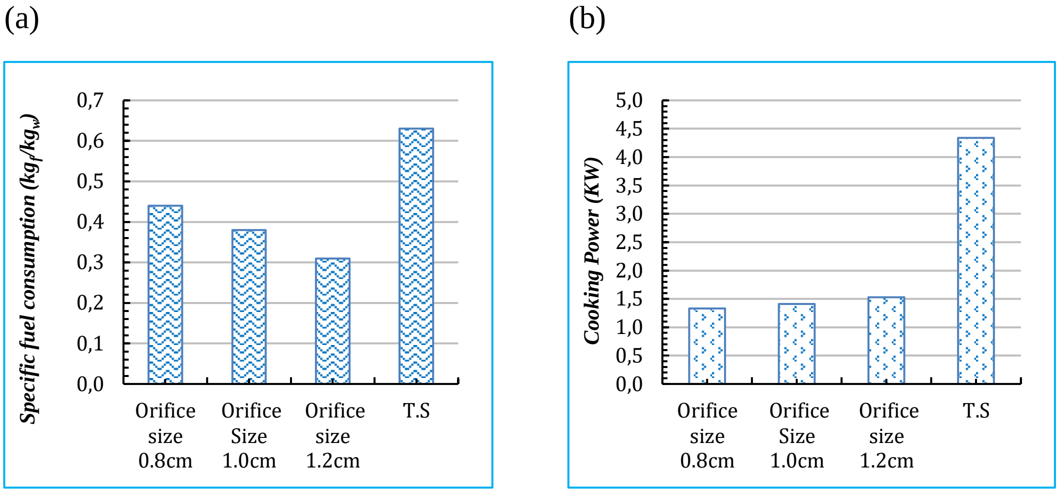

Figure 4 - (a) Specific fuel consumption comparison (b) Cooking power comparison at various orifice sizes

3.4 Burn rate

Burn rate is the weight of biomass that burns over a given period in air. Compared to the improved version, the traditional stove, known as Adugan, exhibits a quicker burn rate because it uses more fuel. Meanwhile, the burner featuring the smallest orifice size demonstrates the slowest burn rate. Figure 5(a) illustrates the increase in burn rate, which ranges from 0.068 *kg/min* for the burner with an orifice size of 0.8 *cm*, to 0.22 *kg/min* for the traditional stove (Adugan).

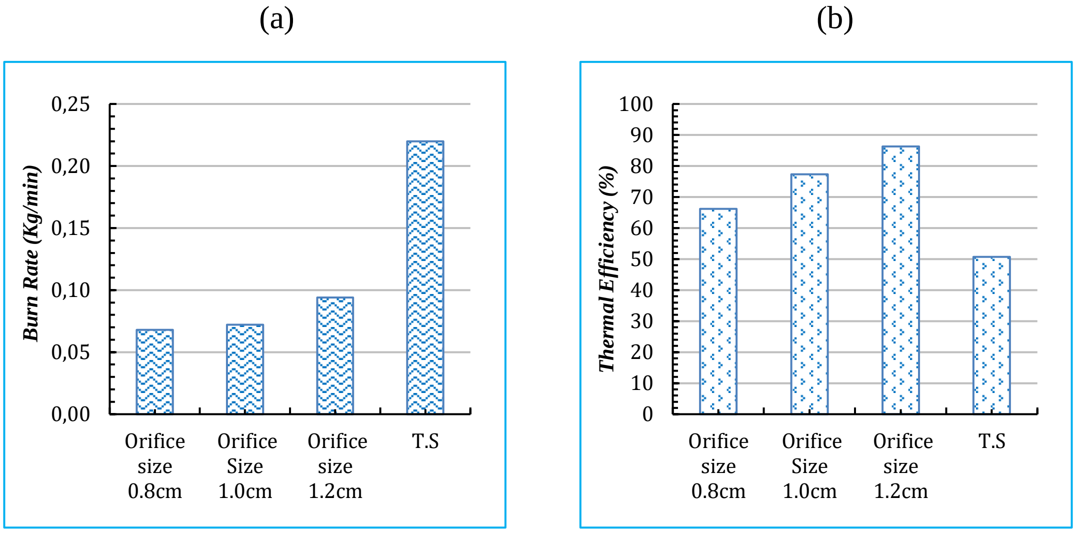

Figure 5 - (a) Variation of burn rate (b) thermal efficiency at different orifice

3.5 Thermal efficiency

Figure 5(b) illustrates a comparison of thermal efficiency among burners with varying orifice sizes and a traditional stove (Adugan). It is observed that the burner featuring the largest orifice size demonstrates the greatest efficiency, attributed to reduced fuel usage. Specifically, the thermal efficiency of the improved stove with orifice sizes of 1.2 cm, 1.0 cm, and 0.8 cm is enhanced by 70.2%, 52.4%, and 30.5%, respectively, when compared to the traditional stove.

3.6 Flue gas emission

Figure 6 presents the findings of the experiment conducted at various intervals. Initially, measurements were recorded while the stove's fire was intensely burning at the upper edge, located between the pot and the stove's skirt. Subsequent readings were taken following the water's boiling point and at the conclusion of the experiment. The data clearly illustrate that the traditional stove (Adugan) releases higher levels of CO parts per million (ppm) compared to the stoves featuring varying orifice dimensions. This increased emission is attributed to the Adugan's expansive surface area and specific design, which hinder the complete combustion of the biomass fuel.

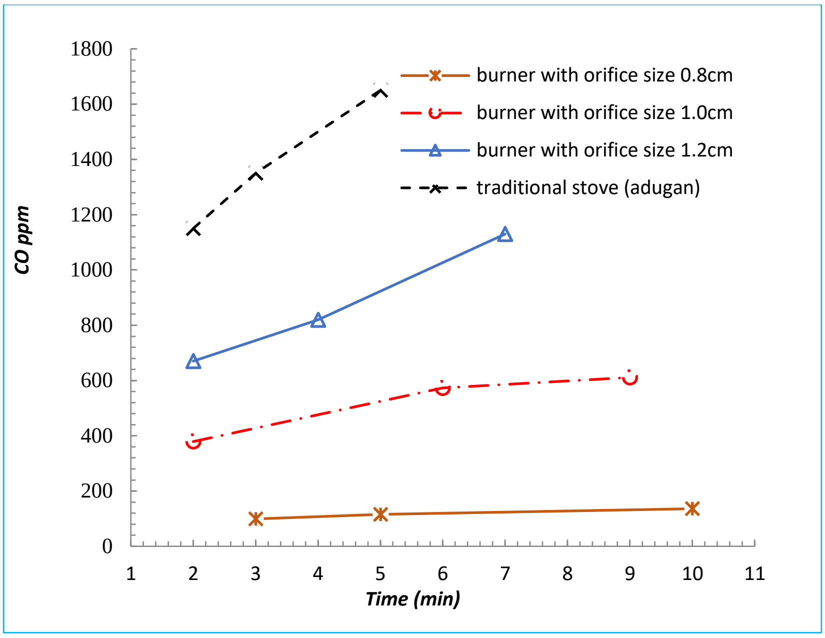

Figure 6 - Variation of CO (ppm) emission with time

4. Conclusion

In this study, we have been able to identify burner orifice sizes implications; and thus investigated the effect of same on the performance characteristics and carbon neutrality profile of traditional stoves. Results presented the improved cookstove with burner orifice size of 1.2 *cm* as the optimal choice; as it offers the highest thermal efficiency, lowest specific fuel consumption and lowest CO ppm among the tested sizes. This suggests it is the most efficient in terms of energy use, heat transfer and environmental friendliness. Although the traditional stove provides higher cooking power and shorter cooking duration, its lower thermal efficiency, higher fuel consumption and higher CO ppm make it less sustainable and economical over time. Therefore, for a balance of energy sustainability model, the 1.2 *cm* burner orifice size is recommended.

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