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Analysis of Thermal Performance of Improved Wood Burning Stoves Using Different Wood Species Found in Northern Nigeria

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Abstract— *The analysis of thermal performance of three different improved wood burning stoves was conducted according to standard laboratory procedures using Tsirir, Marke, Aduwa, Chediya, Kalgo and Kuka fuel woods. The growing gap between availability and demand for firewood, coupled with the scarcity and increasing price of fossil fuels, the poor thermal performance and pollution caused by traditional stoves as a result of burning inappropriate wood species, forced the attention of this work on the thermal characteristics of some of these wood species. Analysis of the results revealed that Kuka exhibited the highest heat content (25.8J/kg) followed by Tsirir (24.0J/kg) with Kalgo having the least calorific value of 15.8J/kg. Also, Kuka exhibited the highest flame temperature of 510^{0}C, while others such as Tsirir, Marke, Kalgo, Chediya and Aduwa has 478^{0}C, 430^{0}C, 302^{0}C, 436^{0}C and 472^{0}C respectively. Oxygen index analyses revealed that Kalgo exhibited the highest value of 32% while others exhibited lower values. In the three stove samples Kuka has the highest fuel consumption rate and Chediya shows the highest combustion temperature in stove 2 and 3. For all stove samples, combustion temperature increases with fuel wood burning duration with stove 2 having the highest fuel wood combustion efficiency in all the fuel wood tested while sample stove 1 and 3 show varying combustion efficiencies. The adoption and largescale propagation of improved wood stoves coupled with utilization of appropriate wood species could help in improving the health of rural and urban users and in making a more efficient utilization of the available firewood resources.*

Keywords— *Calorific value; Combustion; Flame temperature; Fuel wood; Oxygen index.*

I. INTRODUCTION

It has been established that the progress of civilization from the primitive stage to the highly developed technological era is linked with man's utilization of wood and wood products. For thousands of years, man has become so much committed to the use of wood to the extent that even the processes of economic development in the highly developed countries such as USA, Britain, Sweden, Germany, Finland, Holland etc., could come to standstill if deprived access to usage of woods and other forest products. Wood and other forest products are greatly used for paper, films, household heating, industrial heating, melting of ores, construction of furniture, farm implements, to mention but a few (Garba et al, 1997).

In northern Nigeria, wood is extremely used for domestic purposes (Maishanu et al, 1990). The major problem facing this issue is the fast disappearance of our forest tree species caused by the forest poachers and the threat of desert encroachment. Apart from desertification threat, the atmospheric surrounding which is full of burning material tends to be highly polluted with particulates (typically Carbonaceous and Aerosol materials), some very hot and toxic gases, for example, carbon monoxide, hydrogen sulphide etc., These could lead to the reduction of oxygen volume in the atmosphere, and can cause a major problem to the world.

The use of wood stove is one of the most basic human needs that must be met in adequate quantity to sustain life with minimum health hazard. The 3 - stone fires are the most commonly used means of cooking in most households in Nigeria and Africa at large. Considerable amount of heat is wasted in its use and the smoke generated from burning fuel wood has been found to be harmful to its users. Improved wood burning stoves have been proposed to arrest the effect of smoke generated on the user and reduce its high fuel consumption. The improvement of this stove means improving the efficiency in utilization of the fuel. The present practice of using 3 – stone type wood stove is very time consuming and possess a lot of health hazards. The aim of this study is to analyze the combustion characteristics of some selected fuel wood species.

II. MATERIALS AND METHODS

2.1 Materials

2.1.1 Brief description of the fuel wood species

Chediya *(Ficus thononiugii)*: This is also known as 'Chediya' in Hausa language and is commonly found in the northern part of Nigeria such as Sokoto, Zamfara, Kebbi and Bauchi states. The bark is smooth, pale brown or grey in colour.

Aduwa (Balanities aegyptiaca): This specie is also known as 'Aduwa' in Hausa. In Nigeria, it is found in Kwanar Dan Gora in Kano state, Babban-mutum in Katsina state, Illela in Sokoto state and Yankari games reserve in Bauchi state. The wood is pale yellow, bark with vertical fissures, slash – pale yellow.

Kuka (Adonsonia digitata): It is fondly called 'Kuka' in Hausa language. It is a habitat of the savannah where it is usually planted or preserved. The fully grown tree is about 24.38 metres.

Tsirir (Combretum nigricans): In Hausa language the tree is known as 'Tsirir'. It is mostly found in drier areas of Northern Nigeria, such as Sokoto and some part of Bauchi state. The tree is about 7.63 metres in average height when fully grown. The bark is nearly smooth, pinkish – brown. The surface is often fibrous in texture and has a characteristics gum which is reddish in colour.

Marke (Anageissus leocarpus): This tree is known as 'Marke' in Hausa language. It is found in most parts of the Savannah areas from the driest regions to the borders of the forest zone.

A fully grown tree is about 27.45 metres high, with branches ascending usually from low down and often dropping at the ends. The bark of the tree is grey to the pale brown, while the fuel wood is greyish outside dark brown at the heart and very hard.

Kalgo (Piliosigma reticulatum): It is commonly found in Bauchi, Sokoto and other parts of tropical areas of Nigeria. It is also known as 'Kalgo' in Hausa language. The size of the tree when fully grown is about 9.15 metres high. The bark is dark grey sometimes rust coloured. Its fuel wood is brown, stronger and tough.

2.1.2 Preparation of fuel wood species

The samples were obtained within the North – Eastern part of Nigeria and dried under the sun for four weeks before being used. The samples were identified in the biological laboratory of Abubakar Tafawa Balewa University, Bauchi.

2.1.3 Description of wood stoves

The stove(s) used as the experimental test rigs consist of the following parts which are adopted from Abubakar (2011) and Lawal et al., (2021):

i. *Stove body:* This is made with locally available clay with rice husk, saw dust and wire mesh as binding materials. A firebox entrance is provided at the front end, with holes on top (pot holes).
ii. *Fire box:* This is also called the combustion chamber where the fuel woods are burnt.
iii. *Pot holes:* This is provided on the top of the stove body to serve as a place for mounting the cooking pots (exit flue opening(s)).
iv. *Baffle:* This is provided under the second pot hole to ensure maximum heat efficiency and flame stabilization.
v. *Damper:* This regulates the flow of air and gases through the stove. It is incorporated to the chimney and appropriately adjusted to open or completely block the chimney.
vi. *Chimney:* This is incorporated according to the required chimney height design in the form of short cylinders and it provides draught to draw air into the firebox.
vii. *Grate:* This is made of wire mesh in the fire box. This divides the fuel wood entrance into two so that air can get into the combustion chamber.

2.1.4 Configuration of wood burning stoves

The stoves were adopted from Abubakar (2011) and Lawal et al., (2021).

1. *Stove 1:* The stove size is 500mm x 300mm x 250mm and has a wall thickness of 30mm with no grate. This stove is an adoption of the wood burning from Sokoto Energy Research Center (SERC).
2. *Stove 2:* The stove size is 450mm x 250mm x 200mm and the stove wall thickness is 50mm. The grate has a dimension of 100mm x 80mm x 65mm and a firebox inlet entrance projected outside the combustion chamber. It is incorporated with a secondary air inlet below the firebox inlet entrance (Adisa, 2003).
3. *Stove 3:* It is similar to stove one but it is incorporated with a grate and the stove size is 500mm x 300mm x 250mm and the wall thickness is 40mm. The stove is an adoption of the wood burning stove from the Sokoto Energy Research Center (SERC).

2.2 Experimental Methods

2.2.1 Experimental procedures

i. *Limiting oxygen index (LOI):* ASTM D2863 methods was adopted and the relationship of the limiting oxygen index and the mixture of oxygen and nitrogen are given as

$$LOI(\%) = \frac{O_2}{O_2 + N_2} \times 100 \quad (2.1)$$

Where; $O_2 =$ Volumetriv flow of oxygen (cm^3/min), $N_2 =$ Volumetric flow of nitrogen (cm^3/min).

ii. *Calorific value:* The calorific value or heat liberated is determined by using fuel/food calorimeter model LO 4-340, manufactured by Griffin and George Limited, England.
iii. *Flame temperature:* A German made HBC. Geroz, Watt metre, model 4014 connected to thermocouple was used to measure the flame temperature of each fuel wood. The probe of the thermocouple is positioned at the blue zone of the flame of each combusting fuel wood samples. The test procedures are repeated for each wood sample and the mean noted.
iv. *Wind velocity:* The values of the daily average wind velocity for Bauchi metropolis was collected from the Metrological department to cover the period of the experiments.

2.2.2 Performance evaluation of wood burning stoves

The water boiling test (WBT) was adopted. Pieces of fuel wood samples were weighed in a weighing balance before being used to boil one liter of water in each stove sample. The fire is extinguished when the water boils completely. To determine the weight of fuel wood consumption required to boil one liter of water, the remaining wood pieces is collected and weighed and the time taken for the water to boil was also observed with a stop watch and recorded.

2.2.3 Determination of fuel wood combustion temperature for stove samples

The fuel wood species were used as fuels for the sample stoves. The flame temperature of the fuel wood under study was measured with the aid of a German made HBC, Geroz Watt Metre, model 4014 connected to thermocouple. The thermocouple's probe was positioned at four different equidistant points, and the readings of the combustion temperature were taken after every minute for an experimental duration of twenty minutes.

III. Results

3.1 Results of thermal and combustion properties of fuel wood

From table 1 and figure 1, *Kuka* exhibited the highest heat content (25.8J/kg) followed by Tsirir (24.0J/kg). Figure 2 revealed that *Kuka* exhibited the highest flame temperature of 510^{0}C, while others such as *Tsirir, Marke, Kalgo, Chediya* and *Aduwa* has 478^{0}C, 430^{0}C, 302^{0}C, 436^{0}C and 472^{0}C respectively.

Oxygen index analyses also shows that Kalgo exhibited the highest value of 32% while others exhibited lower values.

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TABLE 1: Properties of fuel woods

Properties	*Tsirir*	*Marke*	*Kalgo*	*Chediya*	*Aduwa*	*Kuka*
Moisture content	-	-	-	-	-	-
Calorific value (J/kg)	24.0	18.5	15.8	20.0	20.4	25.8
Flame temperature (^{0}C)	478.0	430.0	302.0	436.0	472.0	510.0
Oxygen index (%)	24.0	25.0	32.0	30.0	25.0	23.0
Air velocity (m/s)	33.9	33.9	33.9	33.9	33.9	33.9
Volume of water (l)	1.0	1.0	1.0	1.0	1.0	1.0

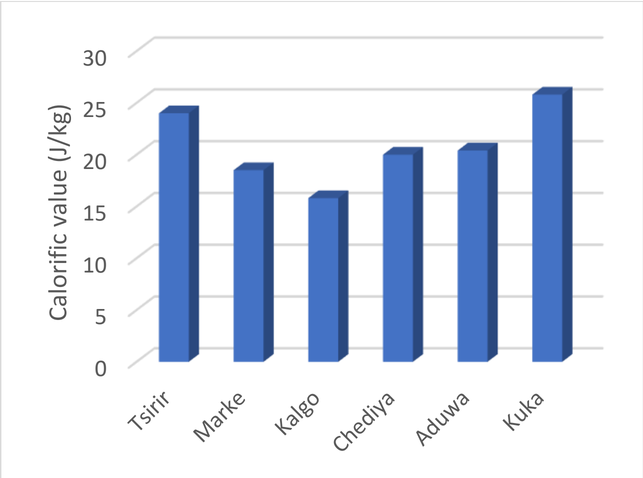

Figure 1: Calorific values of wood fuels

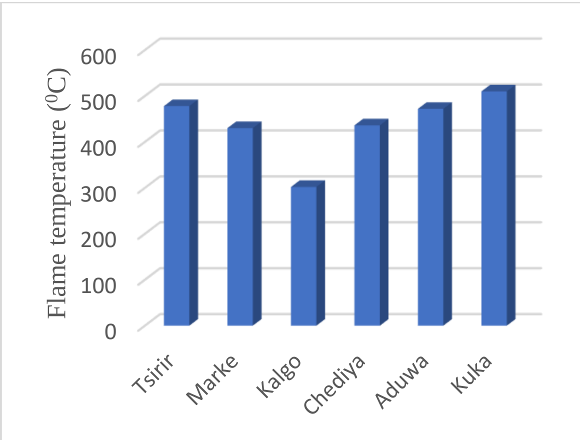

Figure 2: Flame temperatures of wood fuels

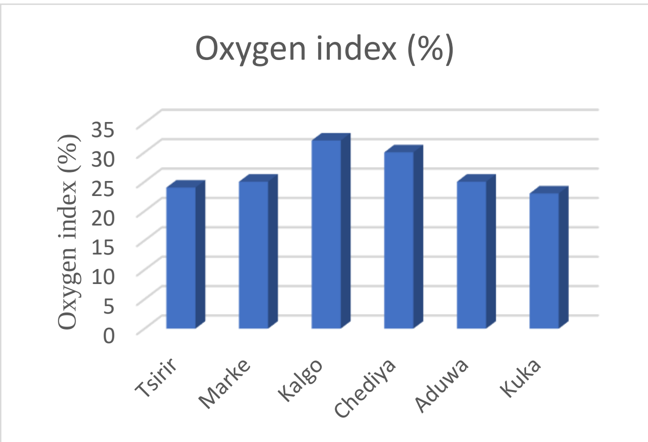

Figure 3: Oxygen index of wood fuels

3.2 Results of Performance of Wood Burning stoves

From table 2, stove 1 has a significant higher fuel consumption rate for the case of *Kuka* (i.e., 29.80g/min) closely followed by *Chediya, Aduwa, Kalgo, Marke, and Tsirir* with a fuel consumption rate of 17.39g/min, 15.51g/min, 12.0g/min, 10.94g/min and 5.53g/min respectively.

Stove 2 also shows *Kuka* with the highest fuel consumption of 35.68g/min and closely followed by *Marke, Kalgo, Aduwa, Chediya, and Tsirir* with values of 30.95g/min, 18.05g/min, 9.13g/min, 8.30g/min and 7.30g/min respectively.

The result of the analysis using stove 3 also revealed that *Kuka* (28.86g/min) exhibited the highest fuel wood consumption rate with *Tsirir* having the least fuel consumption rate.

Figure 4 shows the fuel consumption rate of the three different stoves.

TABLE 2: Effect of fuel wood burning rate of stove types at a mean air velocity of 33.9m/s

Types of fuel wood	Fuel wood burning rate (g/mins)		
	Stove 1	Stove 2	Stove 3
Tsirir	5.53	7.30	10.89
Marke	10.94	30.95	21.69
Kalgo	12.00	18.05	16.94
Chediya	17.39	8.30	13.65
Aduwa	15.51	9.13	15.09
Kuka	29.80	35.68	28.86

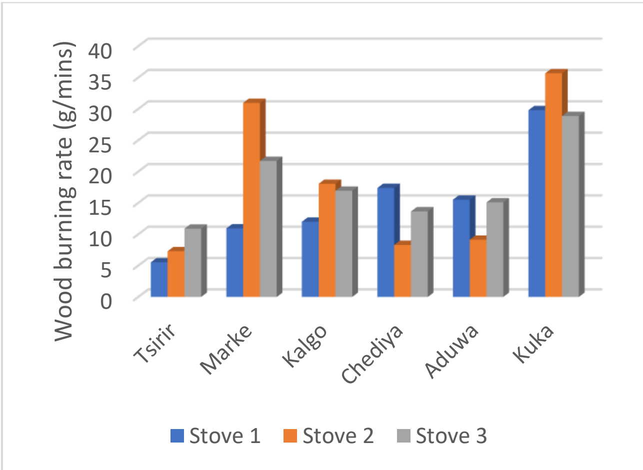

Figure 4: Profile of wood burning rate

3.3 Results of the mean fuel wood combustion temperature in stove samples

Table 3 and figure 5 show that Aduwa exhibited the highest mean combustion temperature of 104.95^{0}C for sample stove 1 at maximum burning duration of twenty minutes. While, the means combustion temperature of Tsirir (102.50^{0}C), Chediya (98.70^{0}C), Kuka (95.73^{0}C), Marke (92.22^{0}C) and Kalgo (87.05^{0}C) follows respectively.

In the case of sample stove 2, the results in table 4 and figure 6 revealed that Chediya exhibited the highest mean combustion temperature of 126.23^{0}C, while Kuka (122.85^{0}C), Aduwa (116.10^{0}C), Tsirir (115.40^{0}C) Marke (114.53^{0}C) and Kalgo (108.40^{0}C) are presented in the descending order for the same experimental duration.

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TABLE 3: Wood burning temperature of different wood types in sample stove 1

Types of fuel wood	Burning duration (mins)	Combustion temperature (^{0}C)				
		T1	T2	T3	T4	Mean
Tsirir	5	19.2	23.4	29.8	33.2	26.40
	10	53	65	71.2	81.4	67.65
	15	80.7	80.2	89.2	90.1	85.05
	20	98.2	100.2	101.2	110.4	102.50
Marke	5	19.8	20.6	24.8	26	22.80
	10	44.4	52	55.1	65.4	54.23
	15	70.1	83.4	86.2	93.2	83.23
	20	78.4	90.1	99.3	101.3	92.28
Kalgo	5	17.8	18.5	23	24.2	20.88
	10	39.5	45.6	77.5	80.3	60.73
	15	60.7	65.1	79.4	89	73.55
	20	75.8	79.9	94.1	98.4	87.05
Chediya	5	32.1	33.6	39.9	43.1	37.18
	10	74.8	89.3	98.6	102.4	91.28
	15	76.9	82.2	100.9	102	90.50
	20	85.1	92.3	104.6	112.8	98.70
Aduwa	5	28.6	35.3	38.4	40	35.58
	10	68.4	77.8	89.2	98.7	83.53
	15	76.3	82.2	90	105.6	88.53
	20	99.2	94.6	111.1	114.9	104.95
Kuka	5	20.9	29.2	30.9	38.2	29.80
	10	53.3	69.3	80.6	95.7	74.73
	15	66	73.3	85.4	96.1	80.20
	20	80.1	89.6	100.1	113.1	95.73

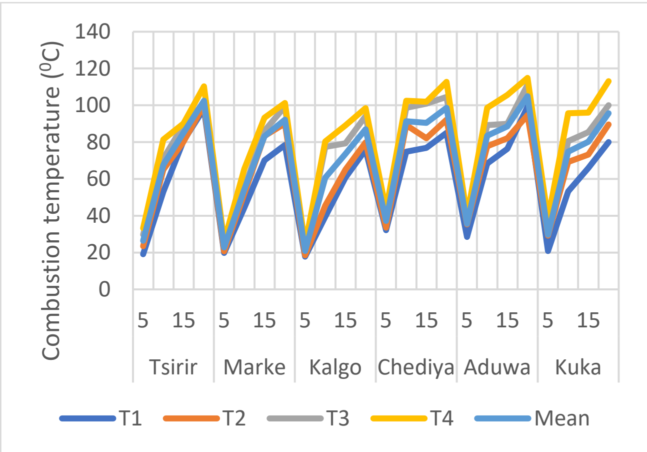

Figure 5: Fuel combustion temperature for stove 1

Results of mean combustion temperature of sample stove 3 in table 5 and illustrated in figure revealed that Chediya demonstrated the highest combustion temperature of 112.03^{0}C with Tsirir having the least combustion temperature of 87.55^{0}C.

Figures 5, 6 and 7 show that for all stove samples, combustion temperature increases with fuel wood burning duration.

TABLE 4: Wood burning temperature of different wood types in sample 2

Types of fuel wood	Burning duration (mins)	Combustion temperature (^{0}C)				
		T1	T2	T3	T4	Mean
Tsirir	5	31.6	35.4	63.8	69.3	50.03
	10	79.1	88.4	106.3	115.5	97.33
	15	85.8	97.8	115.6	129.1	107.08
	20	95.3	108.7	121.7	135.9	115.40
Marke	5	27.8	35.8	41.3	43.8	37.18
	10	69.7	89.5	103.2	109.6	93.00
	15	76.8	95.8	113.7	118.9	101.30
	20	96	107.3	124.6	130.2	114.53
Kalgo	5	23.5	25.4	44	47.3	35.05
	10	58.8	63.5	97.8	105.2	81.33
	15	75.7	78.6	106.4	110.3	92.75
	20	94.6	98.3	118.2	122.5	108.40
Chediya	5	33.8	36.9	45.2	47.9	40.95
	10	84.4	92.2	113.1	119.7	102.35
	15	97	100.8	119.2	125.8	110.70
	20	114.1	118.6	132.4	139.8	126.23
Aduwa	5	26.6	33.3	46.7	49.4	39.00
	10	66.5	83.2	116.8	123.6	97.53
	15	74.8	91.4	121.1	129	104.08
	20	93.6	107.5	127.5	135.8	116.10
Kuka	5	32.5	37.2	48.4	51.8	42.48
	10	81.3	92.9	121	129.5	106.18
	15	87.2	96.1	138.3	145.2	116.70
	20	91.8	101.2	145.6	152.8	122.85

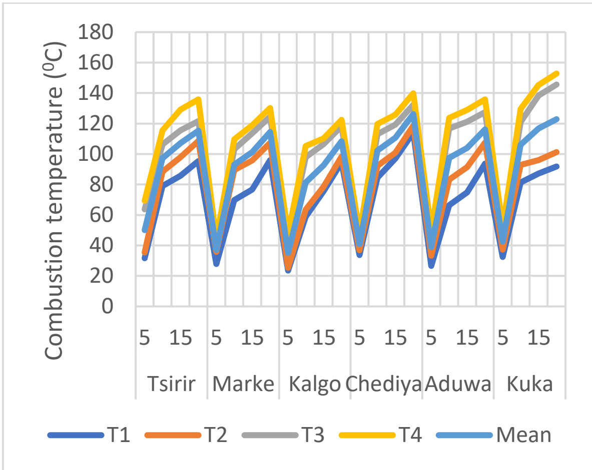

Figure 6: Fuel combustion temperature for stove 2

TABLE 5: Wood burning temperature of different wood types in sample stove 3

Types of fuel wood	Burning duration (mins)	Combustion temperature (^{0}C)				
		T1	T2	T3	T4	Mean
Tsirir	5	23.3	24.2	28.3	34.9	27.68
	10	52.2	60.5	70.7	87.2	67.65
	15	61.4	72.4	81.8	97.8	78.35
	20	68.2	80.4	92.9	108.7	87.55
Marke	5	20	25.2	28	31.7	26.23
	10	50.1	63.1	74.1	89.3	69.15
	15	80.3	83.8	89.5	93.33	86.73
	20	89.2	93.1	99.5	103.7	96.38
Kalgo	5	40.2	58.5	70.2	89.2	64.53
	10	53.2	58.5	70.2	89.2	67.78
	15	68.6	74.6	84.8	96	81.00
	20	85.8	93.2	99.8	106.7	96.38
Chediya	5	24.3	28.1	34.2	39.5	31.53
	10	60.8	70.2	85.6	98.7	78.83
	15	78.8	86.2	94.6	105.1	91.18
	20	98.5	107.7	118.3	123.6	112.03
Aduwa	5	25.8	31	37.4	41.2	33.85
	10	64.4	77.5	93.4	102.9	84.55
	15	70.6	79.6	96.4	107.3	88.48
	20	88.3	93.6	103.6	112.9	99.60
Kuka	5	26	30.5	33.4	37.8	31.93
	10	65.1	76.2	83.6	94.6	79.88
	15	72.2	77.5	85.1	99.8	83.65
	20	80.2	86.1	94.6	105.8	91.68

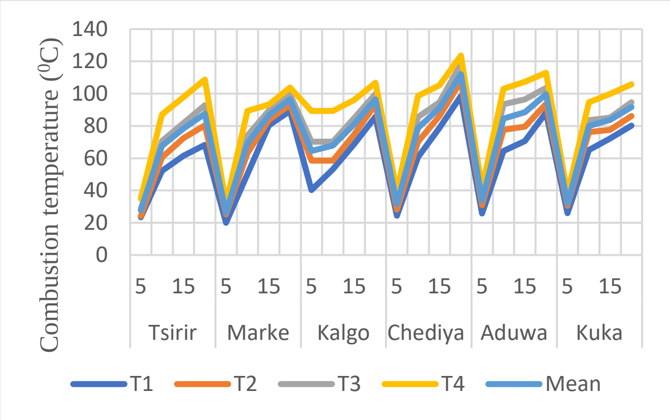

Figure 7: Fuel combustion temperature for stove 3

3.4 Results of wood burning efficiency in stove samples

Figure 8 revealed that sample stove 2 produced the highest fuel wood combustion efficiency in all the fuel wood tested while sample stove 1 and 3 show varying combustion efficiencies. Chediya has the highest combustion temperature.

Types of fuel wood	Burning duration (mins)	Mean Combustion temperature (^{0}C) for stove		
		1	2	3
Tsirir	5	26.40	50.03	27.68
	10	67.65	97.33	67.65
	15	85.05	107.08	78.35
	20	102.50	115.40	87.55
Marke	5	22.80	37.18	26.23
	10	54.23	93.00	69.15
	15	83.23	101.30	86.73
	20	92.28	114.53	96.38
Kalgo	5	20.88	35.05	64.53
	10	60.73	81.33	67.78
	15	73.55	92.75	81.00
	20	87.05	108.40	96.38
Chediya	5	37.18	40.95	31.53
	10	91.28	102.35	78.83
	15	90.50	110.70	91.18
	20	98.70	126.23	112.03
Aduwa	5	35.58	39.00	33.85
	10	83.53	97.53	84.55
	15	88.53	104.08	88.48
	20	104.95	116.10	99.60
Kuka	5	29.80	42.48	31.93
	10	74.73	106.18	79.88
	15	80.20	116.70	83.65
	20	95.73	122.85	91.68

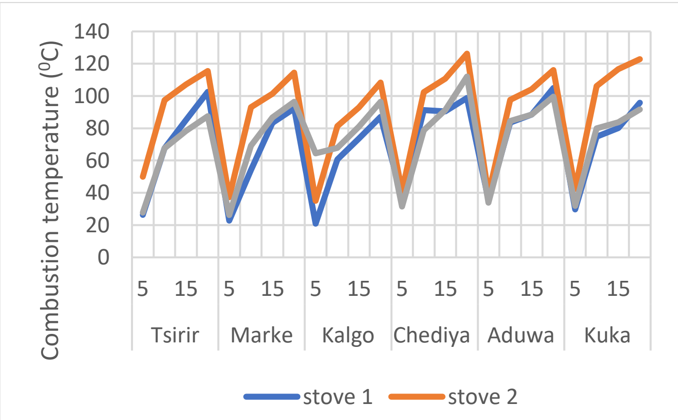

Figure 8: Mean Combustion temperatures of the three sample stoves

IV. Discussion of Results

4.1 Discussion on Thermal Properties of Fuel Wood

It was observed that the calorific value and flame temperature of Kuka fuel wood is higher than the other fuel woods tested. It could also be seen that the result of the oxygen index is higher with Kalgo and least with Kuka. The implication of the outcome of these results is that, the higher the calorific value of a fuel wood, the higher the likely hood to generate higher flame temperature, and the lower oxygen index is required to support the combustion of the fuel woods. Moisture content which influenced the combustion efficiency and characteristics of fuel woods may also have affected the performance of the fuels.

4.2 Discussion on Fuel Wood Consumption Rate

Analysis of fuel wood combustion rate showed that Kuka exhibited the highest combustion rate when compared to others with Tsirir having the least. The fuel wood consumption rate is highest for sample stove 2 with 33.9m/s as mean air velocity. The rate of burning (and hence the rate of heat released) is determined by the manner in which the air required for combustion gets supplied to the burning wood. Therefore, the finding that a proportional relationship exists between fuel wood consumption rate (and burning rates) and air supply seems relevant in the present context. It was further noted that if the burning phase is steady, then burning rate is characteristic of flaming combustion, and is dependent on the measured airflow through the air vent under the fire box.

4.3 Discussion on Fuel Wood Combustion Temperature

Fuel wood combustion temperature in table 3, 4 and 5 showed that Aduwa, Chediya and Chediya fuel wood generated the highest combustion temperatures within the combustion chamber of sample stove 1, 2 and 3 respectively. However, the result is not consistent with the interpretation of the calorific value and flame temperature of Kuka, Tsirir, and Aduwa in table 1 and figures 1 and 2 respectively due to combustion temperature variation influenced by the size of the wood pieces, its geometry, voilage and moisture content.

Further, it was also noted that the outcome combustion temperature reading for sample stove 2 in table, clearly indicated that a more efficient combustion leading to higher combustion temperature has taken place.

4.4 Discussion on Combustion Efficiency of Wood Burning Stoves

From the results, sample stove 2 exhibited higher combustion efficiency than the other two stoves. This is attributed to the design configuration of the cook stove which includes chimney and air vent to generate secondary air in addition to the primary air.

V. Conclusion

The growing gap between availability and demand for firewood, coupled with the scarcity and increasing price of fossil fuels, the poor thermal performance and pollution caused by traditional stoves as a result of burning inappropriate wood species, forced the attention of this work on the thermal characteristics of some of these wood species. These factors which include calorific value, flame temperature and burning rates led to the development of some efficient wood burning stoves. The adoption and largescale propagation of improved wood stoves coupled with utilization of appropriate wood species could help in improving the health of rural and urban users and in making a more efficient utilization of the available firewood resources.

From the study of combustion properties of different wood fuels using different stoves, the following could be concluded from the results of the study.

1. Kuka and Tsirir exhibited higher calorific values and flame temperature than Aduwa, Chediya, Kalgo and Marke fuel wood.
2. Conversely Kuka and Tsirir demonstrated lower oxygen index than Kalgo, Chediya, Marke and Aduwa fuel woods respectively.
3. The burning rates of Kuka and Tsirir are higher than Chediya, Aduwa, Kalgo and Marke fuel woods, owing to their higher calorific values, lower oxygen index and weight of the fuel wood pieces and moisture content.
4. The variation in combustion temperature of Aduwa, Chediya in stove 1, 2, and 3 are influenced by the weight of the wood pieces, its geometry and moisture content.
5. Sample stove 2 exhibited better combustion efficiency for all fuel wood samples under study, owing to the incorporation of a vent chimney and inlets for inflow of primary and secondary air to circulate and produce stoichiometric combustion.

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