Particle size effects on combustion properties of hardwood charcoal

O. J. Ijabo* , J.O. Awulu

(Department of Agricultural and Environmental Engineering, University of Agriculture, Makurdi, Nigeria)

Abstract: Fish morphormetric parameters namely; length, thickness, width at several points and weight were determined as a prelude and were used to design the furnace-dryer for investigating the effects of hardwood-charcoal particle size on five of its combustion properties under natural convection. The tests were in a dryer at zero load. One-factor experiment at five levels of the charcoal sizes of 10, 20, 28, 37 and 50 mm were used to study four of the properties namely, burn-out time (BOT), burning rate (BR), peak temperature (PT) and the time it takes for the temperature to peak (TTP). For the fifth property which is temperature gradient (TG), a 5×14, two-factor experiment was used. The above charcoal particle sizes form one factor while time after igniting the coal at 20-minutes intervals at 14 levels form the second factor. Each experiment was replicated three times. Temperature readings were taken by calibrating and using a digital multi-meter (MASTERTECH MS8209), at 11 cm spacing interval along the height of the chamber. Charcoal particle size in the range of 10 to 50 mm investigated has linear relationships with the combustion properties of BOT, BR, PT and TTP with high R2 values. The relationship of PT and BOT were directly proportional while that of BR was inversely proportional. Based on the principle of least temperature gradient along the height of the chamber, charcoal in the particle size range of 38 to 50 mm gave a more uniform temperature. Thus for a control requiring uniform temperature in the dryer it would be advisable to use charcoal of 38 to 50 mm particle sizes.

Keywords: charcoal, combustion properties, temperature distribution, fish parameters

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1 Introduction

Charcoal business seems to be a flourishing business in Nigeria judging from the large amounts displayed by the highways and numerous retail shops in the towns. Most of the charcoal in the market is obtained from deliberate felling and charring of hardwood, especially locust bean or mesquite trees. The high demand for charcoal leading to massive felling and burning of hardwood is a great economic waste and is environmentally unfriendly in terms of the carbon released into the atmosphere. The practice is an economic loss because; the prevailing indiscriminate felling of the trees without replacement would lead to deforestation, desertification and eventual extinction of the economic plant species, similar to a situation observed by Feka and Manzano (2008) with mangrove forest in Cameroun. Furthermore, these woods are often charred without utilizing the energy during the charring in a way analogous to gas flaring in Nigeria. In both processes, the atmosphere is polluted and the heat energy wasted.

The immediate concern of this paper is that there is evidence of misuse or underutilization of the heat energy from wood charcoal that need to be checked. For example, some investigators who used charcoal for fish drying reported that the charcoal used as fuel in their furnace was burnt openly (Adebowale *et al*., 2008; Olayemi *et al*., 2013), making energy efficiencies of the system low and their estimations doubtful or difficult. This dual constrain stem from the fact that the wind blows the heat energy wherever it wills and thus dissipating it. Others use wrong spacing between fish trays and fire place in fish drying chambers leading to charring of fish skin and muscle

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***Corresponding author: O. J. Ijabo,** Department of Agricultural and Environmental Engineering Federal University of Agriculture Makurdi, Nigeria. Email: ojijabo@yahoo.com

(Adebowale et al., 2008). Bello and Adegbulugbe (2010) made efforts at determining some combustion properties of charcoal like the chamber peak temperature and the time taken to attain it but failed to specify the size of charcoal utilized. Whereas, Smith (1982) indicated that for charred coal the burning rate partly depends on the particle size and that different sizes of charred coal have specific end uses. For example, pulverized fuels (coal ground to <2 mm in size) are good in power generating plants while crushed coal (< 10 mm in size) is more suitable in small appliances and fluidized-bed combustors. Knowledge of solid fuel of particle sizes of ≥ 10 mm may reveal other specific end uses. Similarly, knowledge of combustion properties of charcoal of sizes ≥ 10 mm would enhance mechanizing, controlling and standardizing of heat processes like drying, roasting and barbequing of yam, plantain, banana, sweet potato, pears, fish, meat and cereals.

This study while discouraging the above mentioned adverse effects of wood charcoal production and business has two broad objectives. One is that while the trees last, the charcoal produced from them should be used optimally and controllably. Two, studies on charcoal are directly applicable to charred coal (Smith, 1982). Hence investigations into combustion properties of wood charcoal can be adapted for determination of similar properties of charred coal.Application of the knowledge of these properties is of immediate economic importance to coal producing countries like Nigeria. When this is known Nigerians can be directed to the use of coal; bearing in mind that Nigeria produced 38.6 metric tons of coal out of the world figure of 9, 586, 278 in 2012 (EIA, 2014). The same country has a three-year mean percentage distribution of households by type of fuel for cooking at national level of 74.1 and 1.1 metric tonnes of wood (whose by-product is the subject of this paper) and coal respectively (NBS, 2011).

The specific objectives of this study are to (1) use some physical properties of fish to design a portable furnace-dryer that can be reproduced in modular form and (2) determine five combustion properties of wood charcoal as affected by particle size.

2 Materials and methods

2.1Fish for preliminary experiment

Thirty (30) catfish, Clarias gariepinus, of assorted sizes were bought from Wadata Market in Makurdi, Benue State, Nigeria. Nine measurements were taken on each fish which are (1) length (mm), (2) width at the head portion (mm), (3) width in the middle portion (mm), (4) width at the tail (mm), (5) depth in the middle (mm), (6) depth at the tail (mm), (7) Weight (kg), (8) diameter at the head when curved (mm) and (9) Diameter perpendicular to the one passing through the head when curved (mm). These data were subjected to descriptive statistics (see Table 1) which in turn were used for designing the trays and the drying chamber.

2.2Charcoal

Three bags of hardwood charcoal of about 50-kg each were obtained from North Bank market in Makurdi, Benue State, Nigeria and were reduced and sorted into the following five particle-size classes by sieving and breaking when necessary: 50, 37, 28, 20 and 10 mm. These particle sizes were chosen to fall outside the scope of pulverized fuels used by Smith (1982) for charred coal and also to have a good number of sizes in the crushed fuel range (to make for robust statistics) within commonly marketed charcoal sizes.

Table 1 Descriptive statistics of fresh catfish parameter

PARAMETER	Length, mm	Head width, mm	Middle width, mm	Tail width, mm	Middle depth, mm	Tail depth, mm	Weight, g	Curved diameterthrough the head, mm	Curved diameter perpendicular to that through the head, mm
Mean	276	51	41	5	37	23	423	78	122
Standard Error	14	2	2	0	2	2	48	4	7
Median	265	51	40	5	38	20	350	72	126
Mode	230	51	37	5	40	20	200	60	90
Standard Deviation	78	12	9	1	11	10	262	24	36
Sample Variance	6,12	149	83	2	119	107	68,593	562	1,285
Kurtosis	0	1	0	4	3	0	2	0	1
Skewness	1	1	0	2	2	1	1	1	1
Range	320	47	36	6	47	40	1,100	91	153
Minimum	140	36	26	3	23	10	100	50	70
Maximum	460	83	62	9	70	50	1,200	141	223
Count	30	30	30	30	30	30	30	30	30

2.3 Experimental design

A one-factor, complete randomized design (CRD) was used to test the effects of particle size on each of chamber peak temperature, time for temperature to peak, charcoal burn-out time and burning rate while a two-factor experiment was used to test the effects of particle size on temperature distribution, i.e. temperature range and gradient, within the height of the chamber as burning progresses with time. The time that temperature readings were taken is one factor at 12 levels starting from zero at 20-minute interval until the charcoal is burnt out (about 240 to 300 minutes).The size of charcoal at the five levels of 10, 20, 28, 37 and 50 mm form the second factor. These experiments were carried out in triplicates and the data subjected to ANOVA using Microsoft Excel statistical package.

2.4 The design of the trays and the furnace-dryer chamber

From personal observation of the investigators a tray that is 0.6 m wide is optimally convenient to handle manually. The permissible safe weight to be lifted manually by one male/female person is 25/15 kg according to WorkSafeNB (2010) and from 3 to 16 or 5 to 25 kg depending on the position of the load relative to the body parts (HWL, 2013).In this context, a weight is considered safe in the sense that it does not cause a musculoskeletal injury (MSI) or musculoskeletal disorders (MSDs) as indicated by WorkSafeNB (2010) and HWL (2013) respectively. Making allowance for a hot tray eight kilogram would be used for the design. Considering the descriptive statistics table of the preliminary experiment given in Table 1, the mean weight of a fresh catfish is 0.42 kg, implying that when the weight of fish is used as the criterion the tray can safely handle19 (8 kg/0.42 kg) fish. Using the larger of the diameters of fish when curved for drying which is 12.23 cm, the theoretical number of fish that can lie along the width of the tray is (0.6/0.1223) 5. This implies that when 19 fishes are arranged 5-in-a-row there would be approximately four rows.

The total dimension of the four rows when the fish are laid diameter to diameter is 49 (4 x12.23) cm, which is the same as the depth of the tray. The vertical distance between the trays is taken to be 11 cm which is made up by adding a clearance of 4 cm to the maximum depth of fish in its middle portion of 7 cm. A six-tray chamber was chosen with the hope that it can easily be modified into modules which can then be similar to multi-chest electrical kilns used in Europe and America (FAO, 2007). Clearance of the first tray from charcoal tray is taken to be 20cm while that between the topmost tray and chimney base is 24 cm. Making for 5 cm clearance between the wall and the tray around the tray, the chamber constructed had the dimensions of 60 × 60 × 110 cm (width × breadth × height). The wall is made of burnt brick with the inside lined with a 3 mm thick shiny aluminium sheet to reflect some of the heat back into the chamber. Thermocouple wires were fixed in the middle of the chamber through pin-holes in the wall to where the drying trays were supposed to be since this experiment used an empty chamber, i.e., at zero load. The thermocouples were at the heights of 20, 31, 42, 53, 64 and 75 cm above the charcoal tray (See Figure 1). The thermocouple temperature readout was by an auto-ranging 5-in-1 digital multi-meter (MASTERTCH MS8209).

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Figure 1 Charcoal fired furnace chamber showing thermocouple positions, T_1 to T_8

2.5 Experimental procedure

Charcoal of a particular size weighing 8.3 kg was evenly spread on the charcoal tray, i.e. 23 kg/m^2 area density. This density allowed for good ignition and uniform temperature distribution at a particular horizontal plane in the chamber. Initial temperatures were taken at the six-height chimney and outside the chamber wall. The temperature outside the chamber wall is referred to as ambient temperature. The charcoal was ignited and the temperature taken at the eight points labelled T_1, T_2, T_3, T_4, T_5, T_6, T_7 and T_8 as in Figure 1 at 20-minutes interval until the charcoal is burnt out. The time it takes each batch of charcoal to burn out, TOB, in minutes was recorded. Combustion rate, kg/s, is given by Equation (1).The temperature gradient along the height of the chamber was approximated by the slope of a straight line fitted to temperature versus height data at different times after ignition of the charcoal.

$$Combustion\ Rate, kg/s = \frac{Quqntity\ of\ charcoal\ in\ the\ tray, kg}{Burn\ out\ time, s} \quad (1)$$

3 Results and discussion

3.1Application of fish parameters to tray and chamber design

Considering the fish parametersin Table 1, its weight has the widest range of 1, 200 g and would be most suitable index for classifying fish.This would be followed by the length of fish. That is to say weight-sorters followed by size, in this case, length-sorters are suggested for sorting of fish based on the dimensions of catfish.

When unsorted fish is presented for drying in the curved form the larger diameter of 12.2 cm is safe for use; in which case the area occupied by fish in a tray can be taken as 0.015 (0.122^2) m^2. On the other hand, for fish drying in a straight form, the product of the length and width at thehead, which is the widest of the three widths, i.e. 0.014 (0.276×0.051) m^2 would be a good index forestimating areas for both chamber capacity and drying area. For the purpose of estimating vertical spacing between trays in a drying chamber a suitable clearance can be added to the deepest middle depth of fish, of 0.07 m.

3.2Overview of chamber condition

There are six trays at different heights.Along the six heights in the chamber 1, 350 (15 time intervals $\times$ 5 sizes $\times$ 3 replications $\times$ 6 locations) temperature readings were taken. Similarly, about 225 corresponding temperature readings were taken atthe chimney and outside wall plus185 relative humidity readings.The mean relative humidity of the exhaust air from the chimney was 24.29%$\pm$ 0.26%.A typical temperature-time profile in the chamber at different heights above the charcoal-fire tray for a batch of charcoal is shown in Figure 2. Figure 3 gives the temperature pattern at the start (20 minutes), peak (180 minutes) and end (300 minutes) of combustion for a particular batch.

3.3Effects of particle size on chamber peak temperature, time for temperature to peak, charcoal burn-out time and burning rate

The lumped ANOVA of the effects of charcoal particle size on chamber peak temperature, time for temperature to peak, charcoal burn-out time and burning rate given in Table 2 shows that particle size has effect on all the four properties at α=0.05.

Table 2 Lumped ANOVA of the effects of particle size on chamber peak temperature, time for temperature to peak, charcoal burning rate and burn-out time

Source of variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Peak temperature	275675	1	275674.8	1147.123	9.36E-18	4.413873*
Within groups	4325.73	18	240.3185			
total	280000.6	19				
Time to peak	61853.3	1	61853.31	360.1754	7.04E-13	4.451322*
Within groups	2919.42	17	171.7311			
total	64772.7	18				
Burning rate	3151.86	1	3151.86	59.84545	3.94E-07	4.413873*
Within groups	948	18	52.66667			
total	4099.86	19				
Burn out time	211820	1	211820.4	606.9997	2.56E-15	4.413873*
Within groups	6281.33	18	348.963			
total	218102	19				

Note: *Indicates that there is significant difference at α= 0.05

common R^2 value of 0.915. Also burn out time has a linear positive variation with particle size having R^2 value of 0.966. The definite equations relating these charcoal combustion properties are given in Table 3. From Table 3, it can be observed that, while the chamber peak temperature and charcoal burn-out time vary positively, the charcoal burning rate has a negative slope. The meaning is that the larger the charcoal size, the higher the chamber peak temperature. Similarly, the larger the particle size of charcoal the longer it takes to burn out. Therefore, in a system

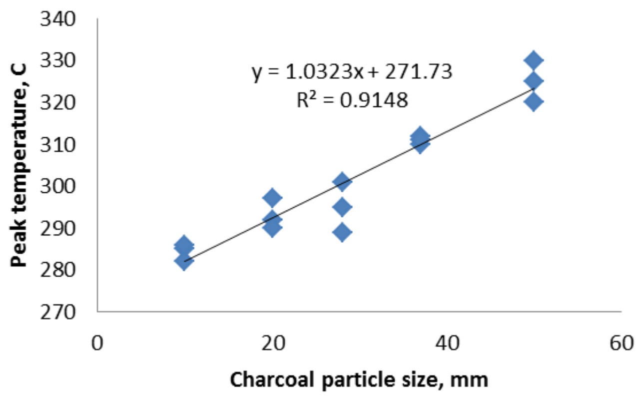

Figure 4 Variation of chamber peak temperature with charcoal particle size

where a particular air temperature and time combination is desired an appropriate charcoal size can be selected for use. Similarly, the knowledge that the smaller the charcoal-size the quicker or faster it burns out can serve as a guide in the feeding rate of the fuel into a charcoal-fired burning chamber. In this way charcoal combustion properties can be used to regulate the drying air temperature or in general the temperature above the furnace tray.

Table 3 Equations of three combustion properties of charcoal as affected by its particle size, X_{cps} (mm)

Equation No	**Equation**	**R^2**	**Definition of property symbol**
(2)	$T_{peak} = 1.032X_p + 271.7$	0.915	T_{peak} = Peak temperature, ℃
(3)	$BR = 0.5949 - 0.0003X_p$	0.915	BR= Burning rate, g/s
(4)	$BOT = 1.455X_p + 225.8$	0.966	BOT = Burn-out time, minutes
(5)	$Y_{TG} = 0.0298 - 0.0004X_{CPS}$	0.95	
(6)	$Y_{TG} = 0.0313 - 0.0004X_{CPS}$	0.9786	Y_{TG} = Temperature gradient, ℃ / m m
(7)	$Y_{TG} = 0.0303 - 0.0004X_{CPS}$	0.979	

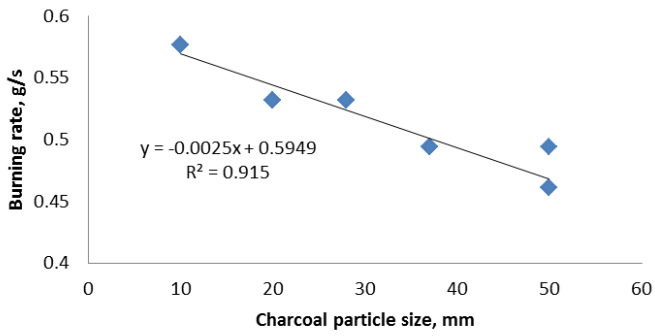

Figure 5 Variation of charcoal burning rate with particle size

3.4Temperature distribution in a charcoal-fired zero-load convection drying chamber

Uniformity of chamber temperature on the horizontal axis is assumed by ensuring a common area density of the charcoal being fired, in this study it is fixed at 23 kg/m^2 which translates to a thickness of about 5.0 cm. Vertical distribution of the generated heat energy as the charcoal burns in the chamber is measured in terms of temperature gradient along the height. The 12 time-intervals of burning beginning from time of ignition of charcoal × five charcoal sizes replicated in triplicates gave 180 gradients. A 2-factor ANOVA of the gradients is given in Table 4 shows that both burning time and charcoal size have significant effect on temperature gradient in the chamber at α= 0.05 using Excel Software. A scatter diagram was used to investigate the pattern of variation of the temperature gradients with each of burning time and particle size but it gave no particular trend. In practical terms, particle size of charcoal can be more easily varied than time of burning in a process. Consequently, the time of burning was ignored and the variation with particle size was further investigated by making a scatter plot of mean temperature gradient versus particle size. Again the plot did not fit any particular curve either but there was an indication that temperature gradient values for charcoal in the particle size range of 10 to 38 mm would give a straight line. Hence when the data for quantity of charcoal retained on the 50 mm sieve were excised, linear curves were obtained as shown in Figure 6 for temperature gradients before and after the peak temperature was attained and overall mean having R^2 values of 0.95, 0.9786 and 0.979 respectively. All the three curves have negative slope as in equations (Equation (5), Equation (6) and Equation (7)), (Table 3) indicating that temperature gradient in the chamber is inversely proportional to the particle size of charcoal being fired in the particle size range of 10 to 50 mm. Since the charcoal retained in sieve having a hole of 38 mm are less than 50 mm but greater than 38 mm, it means that in the charcoal particle size range investigated particles of 38 to 50 mm size would give a more uniform temperature.

Table 4 A two-factor ANOVA of temperature gradient in a charcoal-fuelled furnace chamber

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Burning time	0.097866	4	0.024466	22.60275	3.38E-10	2.583667
Charcoal size	0.045676	11	0.004152	3.836036	0.000663	2.014046
Error	0.047628	44	0.001082			
Total	0.19117	59				

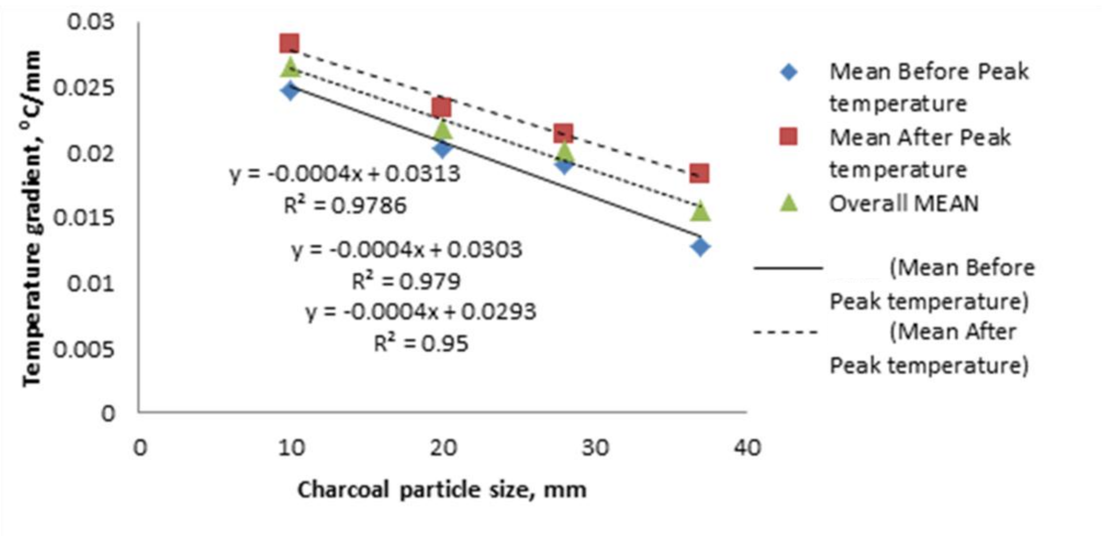

Figure 6 Variation of temperature gradient with charcoal particle size in a furnace-dryer chamber

This size range is also in agreement with the widely accepted size of charcoal briquette indicated by FAO (2015) to be 50 mm in length and thickness of 25 mm approximately.

4 Conclusions

In conclusion, fish parameters have been determined and used for designing a wood charcoal-fired dryer with safe tray sizes according to WorkSafeNB (2010) standard. When the dryer at zero-load was, in turn, used to determine the effects of charcoal particle size on time for charcoal to burn out, chamber peak temperature and the time it takes to peak as well as uniformity of temperature in the chamber above the fire-tray, it showed significant effects.Charcoalparticle size in the range of 10 to 50 mm investigated have linear relationships with the combustion properties of burn out time, burning rate, peak temperature and the time it takes the temperature to peak with high R^2 values.While the relationship with peak temperature and burn-out- time were direct proportion that of burning rate was inverse.Based on the principle of least temperature gradient along the height of the chamber charcoal in the particle size range of 38 to 50 mm gave a more uniform temperature.Thus for a control involving uniform temperature in the dryer it would be advisable to use charcoal of 38 to 50 mm particle sizes.

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