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DESIGN AND PERFORMANCE EVALUATION OF AN ELECTRICALLY POWERED MULTI-PURPOSE FOOD ROASTER

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ABSTRACT
Food roasting is a method and technique used for transforming raw food into edible and tasty food accompanied with change or alteration in the appearance, taste, aroma, shape, or colour of the end product. The traditional method of use of open grill in Nigeria as an example, does not produce consistent end products. This work is about a multi-purpose roasting machine for Maize (Zea maize), Plantain (Musa paradisiaca) and Yam (Dioscorea Sagittifolia). The roasting temperature is allowed to vary between 160-240°C and the distance between the heat source and the item being roasted is also adjustable (50mm-150mm). A 10-50min experiment using ten maize cobs, yam slices and plantain of an average initial weight of 2.9kg, 3kg and 1.16kg respectively led to 6.91%, 6.7% and 9.5% weight loss and 68.4%, 66.1% and 94.1% roasting efficiency.

Keywords: *Multi-Purpose, Food, Roasting, Roasting Conditions*

Nomenclature

B_L	total load on bearing (N)
d	diameter of drilled holes (mm)
D_{FH}	diameter for food housing(mm)
d_i	diameter of chain roller (mm)
D_{mh}	maximum hub diameter (mm)
D_{mv}	maximum mean diameter of food item (mm)
D_o	outer diameter of Sprocket (mm)
E_E	electric motor efficiency (%)
E_F	energy required by the fan (J)
E_{HC}	power of the heating element (W)
E_M	impeller mechanical efficiency (%)
Er	roaster efficiency (%),
FOS	factor of safety
H	plate thickness (mm)
H_{RC}	roasting chamber height (mm).
H_{RI}	inner height of roasting chamber (mm)
H_{RO}	outer height of roasting chamber (mm)
K	multiplying factor
k_1	constant load factor
k_2	periodic lubrication factor
k_3	continuous service conditions factor
k_b	combined factor for bending (Nm)
k_S	service factor for the chain drive
P_B	pressure exerted on the bearing (N/m^2)
p_c	pitch of the chain (mm)
PD	pitch diameter for sprocket (mm)
P_w	power required by the fan (W)
r_1	inner radius (mm)
R_2	outer radius (mm)
R_c	radius for inner constraint (mm)
R_{FH}	radius for food housing cage(mm)
S_s	allowable stress (N/m^2)
T	motor torque (Nm)
t	maximum processing time (sec.)
N_T	number of teeth
T_1	number of teeth on driven sprocket
T_2	number of teeth on driving sprocket
T_e	equivalent twisting moment (Nm)
I_t	roaster insulation thickness (mm)
v	linear velocity (m/s)
V_{L1}	minimum linear velocity (m/s)
V_1	volume of the vertical supports (m^3)
V_{L2}	maximum linear velocity (m/s)
V_2	volume of side supports (m^3)
V_3	volume of the front support (m^3)
V_{DH}	volume of drilled holes (m^3).

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k_t	combined factor for torsion
L	length of chain (mm)
L_{FH}	cylindrical food housing length (mm)
l_{mv}	maximum mean value length of item being roasted (mm)
L_{RC}	roasting Chamber length (mm).
L_{RI}	inner length of roasting chamber (mm),
L_{RO},	outer length of roasting chamber
L	specific latent heat (kJ/kg)
M	bending moment (Nm)
m	mass (kg)
m_1	mass of roasted food (kg)
m_2	mass of unroasted food (kg)
M_b	Bending moment (Nm)
M_t	Torsional moment (Nm)
M_W	Mass of evaporated moisture content (%)
n	number of food in row
N_S	speed of the pinion sprocket (m/s)
N_H	number of drilled holes
P	power (W or kW)
V_f	volume of the frame (m^3)
V_R	volume of roasting chamber (m^3),
V_{RI}	roasting chamber inner volume (m^3)
V_{RO}	roasting chamber outer volume (m^3)
W	chain tension (N)
W_B	breaking load (N)
W_F	average weight of the food being roasted (kg)
W_{RC}	roaster chamber width (mm).
W_{RI}	inner width of roasting chamber (mm)
W_{RO}	outer width of roasting chamber (mm)
W_S	weight of the shaft (N)
x	center distance (m)
μ	coefficient of friction between the materials
ρ	density (kg/m^3)
σ_b	allowable tensile strength (N/m^2)
σ_{ta}	ultimate tensile stress (N/m^2)
t	allowable shear stress (N/m^2)
τ_u	ultimate yield strength (N/m^2)

1. INTRODUCTION

The processing of food items has become an important aspect in human daily consumption of food. It is the methods and techniques used to transform raw ingredients into consumable food or a process by which a raw food is transformed to edible food for consumption by humans or animals either in the home or by the food processing industries [1]. This processing involves application of engineering technology with the aid of food science, to change or alter the appearance, taste, aroma, shape, or colour of the food. Various techniques are available for food processing, most of which are applied in the food industry. These techniques include size reduction, mixing [2] and processing by application of heat [3]. Generally, the size of food materials is often reduced during processing because it reduces the drying time or cooking time as more surface area is exposed to the hot air and gives rise to shorter drying or cooking time [4]. Roasting or grilling is a dry heat cooking process and is one of the most popular methods used for cooking foods. The roasting process tends to evaporate and reduce the moisture content of any type of food, shrinking the fibre and making the food tough [5].

Adisa[6] and Ezekiel *et al.,* [7], designed and developed Charcoal Fired and electric heated Plantain *(Musa Paradisiaca)* roasting machine respectively. The result of the experiment carried out on the roaster showed that plantain was roasted at 185^oC for 21.16 minutes and PAHs concentration of 0.15μg/g with 0.00μg/g carcinogenic PAHs were obtained using charcoal fired plantain roaster while the evaluation made from the electric heated roaster was that the design took 32 minutes to attain its roasting temperature of 200^0C from 30^0Catmospheric temperature. Adegbola *et al.* [8] designed and constructed a domestic basic oven, which was tested with varieties of food item like fish, meat and egg. Oke [9] developed a manually operated multi-purpose roasting charcoal fired roaster and evaluated and tested it with yam, plantain and maize cobs. He found that average roasting time was 15, 30 and 24 minutes in 95%, 97% and 94% of times respectively. Olayinka and Adegboye [10] obtained average roasting time for maize cobs and plantains as 12 minutes and 20 minutes respectively as compared to 15 minutes and 35 minutes for Yam and plantain using convectional roasting method.

Currently, roasting of common delicacies such as maize, plantain and sliced yam on the streets in Nigerian cities and townships have been done using traditional way of roasting, which is roasting over open fire or grill. Despite being very stressful, health-risky and environmentally hazardous, it is still being used. The stress includes regular blowing of air to sustain combustion and regular changing of the position of the food product to prevent it from burning [11] and uneven circulation of heat. Furthermore, lack of appropriate knowledge and inconsistent roasting conditions such as roasting temperature, roasting time and roasting distance from the heat source is commonly observed [12,13]. The goal of this work is to present a design and performance evaluation of an electric powered multi-purpose roaster for maize (*Zea maize*), ripe plantain*Musa paradisiaca*) and sliced yam (*DioscoreaSagittifolia*).

This work is essential as the livelihood of many families depends on this road side roasting business in Nigeria. The aforementioned hazards will also be reduced when enclosed roasting device is used for roasting.

2. METHODOLOGY

2.1. Brief Description of the Developed Machine

The device (figure 1) is a forced convection electrically powered multi-purpose food roaster, for roasting maize, ripe plantain and sliced yam. The external and internal body (the roasting chamber) is made of galvanized iron sheet owing to its resistance to rust or corrosion and does not contaminate the food substance being processed. Fiber wool is stuffed in between inner and outer galvanized sheets and acts to prevent loss of heat (insulation).The roasting chamber houses three cylindrical baskets that rotates with the aid of shaft through the chain drive mechanism. Two fans are installed (on the left and right sides) for forcing air movement. A Nichrome electric heating element is also installed below the baskets. A thermostat controls the temperature of the roasting chamber and installed fans aid circulation of heat in the chamber for homogenous roasting. The chamber is incorporated with chimney to expel moisture released from the food during roasting and a transparent observation window/door made from fiberglass.

2.2. Design Considerations

In the design of this multi-purpose food roaster, food under investigation is expected to rotate at constant speed to receive equal heat circulation and this actually eliminate manual changing of food position. Its design is based on the maximum mean values of maize length: 239mm-273mm, diameter: 44.3mm-48mm, weight: 181.6g-408.6g and plantain length: 181mm-200mm, diameter: 36mm-40mm, weight:116g peeled and 183g unpeeled [14 and 15] and sliced yam with average thickness being 25mm-50mm.

2.3. Component Design

The roasting chamber assembly, the frame or support and the prime mover assembly are considered to be critical for a successful roasting operation. The roasting chamber subassembly consists of the chamber itself, the transparent observation window, 3 cylindrical baskets and the recirculation fans. The frame is treated as a welded cubical body. Its ability to carry weight without failing was further simulated. The prime mover assembly consists of the electric motor, the chain, the sprocket and the shaft carrying the 3 rotating basket and the shaft bearing used in transmitting the torque to the 3 baskets.

2.3.1 The roasting chamber and its accessories

The food basket is shown in Figure 1 with the diameter and length indicated as well. Their values are determined as follows;

(i) Diameter of the basket;

$$D_{FH} = 2R_{FH} = 2(D_{mv} + R_c + clearance) \quad (1)$$

(ii) Its Length;

$$L_{FH} = nl_{mv} \quad (2)$$

The chamber (figure 2) houses the 3 baskets, fans and electric heating element. Its dimension is dependent on the dimensions of the basket, ends clearance and upper and lower clearance.

Width of Roasting Chamber;

$$W_{RC} = L_{FH} + 2(clearance) + 2(insulation\ thickness) \quad (3)$$

Length of the roasting chamber;

$$L_{RC} = 3D_{FH} + (Clearance\ between\ food\ baskets\ and\ the\ chamber\ wall + 2(insulation\ thickness) \quad (4)$$

Height of the roasting chamber; H_{RC} = D_{FH} +maximum roasting distance+ upper clearance +2(insulation thickness) (5)

Volume of Roasting Chamber; $V_R = V_{RO}-(V_{RI}+V_{DH})$ (6)

Outer volume; $V_{RO} = L_{RO}\times W_{RO}\times H_{RO}$ (7)

Inner volume; $V_{RI} = L_{RI}\times W_{RI}\times H_{RI}$ (8)

Volume of drilled holes [10]

$$V_{DH} = \frac{\pi d^2 I_t}{4} \times N_H \quad (9)$$

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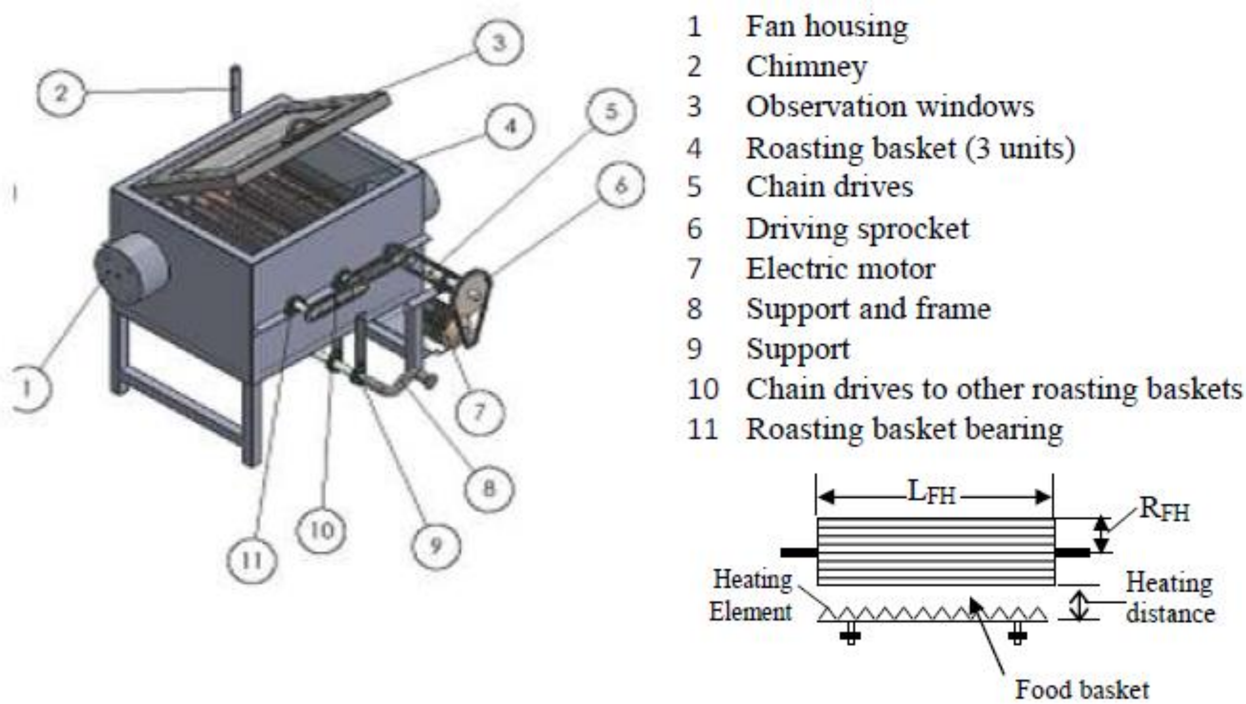


Fig. 1: The Developed Multipurpose Food Roasting Machine

The Fan

The energy required by the fan is given [16] as:

$$E_F = \frac{P_{wt}}{E_E \times E_M} \quad (10)$$

The electric heating element

The heating element was selected to be easily replaceable. A 1000watt Nichrome wire commonly used for open electric cooker was selected for supplying the heat needed for the roasting operations.

2.3.1. The Frame

The frame (Figure 3) consists of front support-3, side support-2 and vertical support-1.

Volume of the frame;

$$V_f = V_1 + V_2 + V_3 \quad (11)$$

The mass of the frame is given as

$$m = \rho \times V_f \quad (12)$$

Normal stress within the frame was deduced using Multi-Physics simulation tool. The maximum normal stress was found to be 16.42MPa and it occurs at the junctions marked X in figure 4 (A). The maximum displacement (0.25mm) and the maximum shear stress (1.412 MPa) occurred at junctions marked Z as shown in figure 4 (B). Most mild steel can take up these stresses without failing.

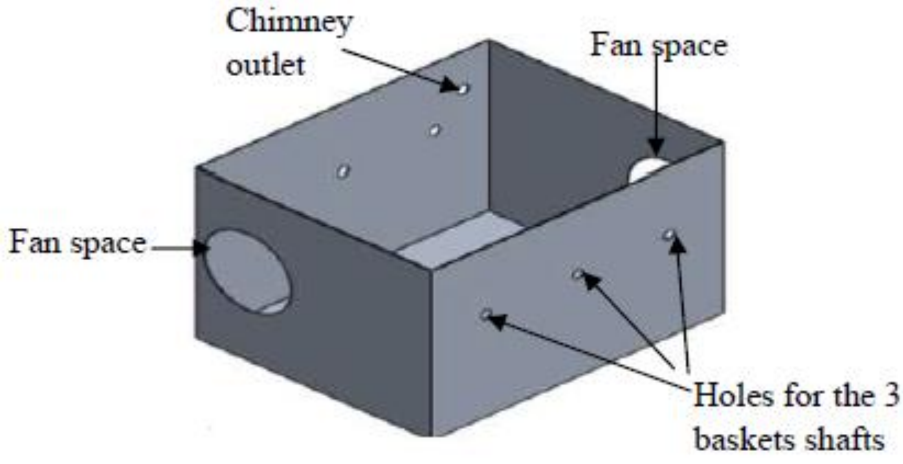


Figure 2: The Roasting Chamber

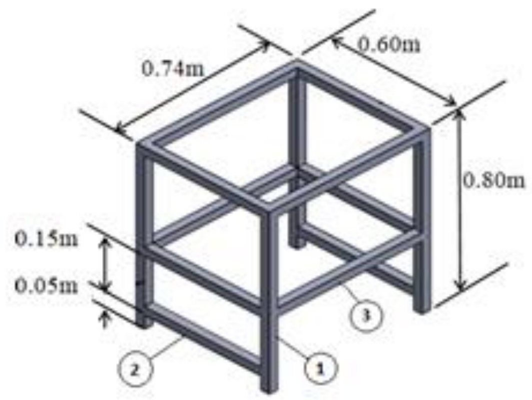
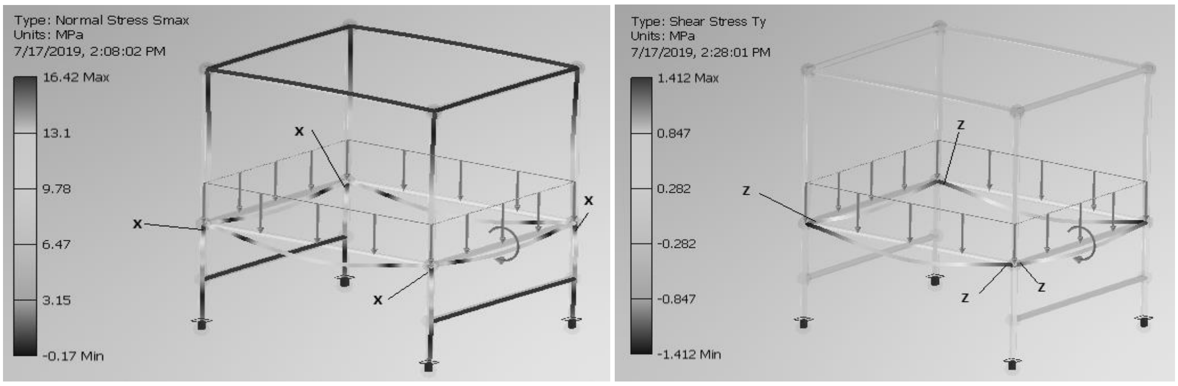


Figure 3: Machine Frame (dimension 800x740x600mm)



A **B**

Figure 4 The normal stress (A) and the shear stress (B) within the frame.

2.3.2. The Prime Mover

Sprocket Design and Selection

The sprocket selection was made alongside with the minimum chain size of 35 with chain pitch (p_c) of 9.52mm and diameter (d_i) of 5.1mm, number of teeth (T_1 =32 and T_2=16)and plain carbon steel material. The plate thickness is given as [17];

D_{mh} = Cos (180/ smaller number of teeth) $\times$ PD – (H+0.05) (13)

But, PD = Constant $\times$ Chain pitch (p_c)

Pitch Diameters (PD) for smaller and bigger sprocket at T_2 =16 and T_1 =32, Constant are 5.1259 for the driver and 10.2023 for the driven sprockets. Hence, for; smaller sprocket, PD = 48.9mm and for bigger sprocket, PD = 97.23mm.

At sprocket plate thickness for selected number of tooth of T_2=16, the maximum hub diameter D_{mh} is 37.7mm according to [17].

The maximum bore diameter of 25.4mm (that is 26mm using standard shaft size) is suitable for the hub diameter between 48.85mm and 97.23mm according to [17] specification. Therefore, the bore diameter is considered as shaft diameter for the sprocket. Outer diameters of driving sprocket and driven sprocket at T_1 =32, and T_2 =16 respectively is given [18] as:

D_o = PD + 0.8d_i (14)

Chain System

Chain power transmission has non uniform linear velocity and hence fluctuating velocity ratio, but varies from maximum to minimum during every tooth engagement (with the sprocket). This fluctuation in chain transmission is minimized by increasing number of teeth on the sprocket.

Maximum and Minimum linear velocities for the chain drive was computed using equation (15) and (16) given by [19] as;

$$V_{L2} = 2618(PD)Cos\frac{180}{T}\,N_s \quad (15)$$

$$V_{L1} = 2618(PD)\,N_s \quad (16)$$

Since the chain pitch is between 12mm and 15mm and designed for low speed of 50rpm (i.e. less than 1 rotation per second), factor of safety for the chain drive is selected as 7as suggested by Khurmi and Gupta [19].

The power transmitted by the chain on the basis of breaking load W_B, is given by this relation [19];

$$P = \frac{W_{B.V}}{FOS.K_s} \tag{17}$$

Where $K_s = K_1K_2K_3$ $W_B = 10.6p_c$ and FOS = 7

The constant load, periodic lubrication and continuous service conditions for chain drive were considered for design. In that scenario, K_1=1, K_2=1.5 and K_3=1.5 according to Khurmi and Gupta [19]. From [17], p_c =9.52 and v = 10.5 (from equation16) and hence K_S =2.25 and P≈ 70W.

Therefore, a 70Watts (0.1Hp) electric motor will be capable of running the roaster mechanism.

The chain tension (W) on driving side according to Khurmi and Gupta [19] is given as

$$W = \frac{W_B}{FOS} \tag{18}$$

The length of the chain is also given as shown in equation (19)

$$L = Kp_c \tag{19}$$

Where

$$K = \frac{T_1 + T_2}{2} + 2m + \frac{\left[cosec\left(\frac{180^o}{T_1}\right) - (cosec\left(\frac{180^o}{T_2}\right)\right]^2}{4m} \tag{20}$$

$$and\ m = \frac{x}{p_c}$$

Where $x = 2R_{FH} +$ distance between each of the roasting baskets = 200mm

(The distance between each of the roasting basket is 50mm).

To accommodate initial sag in the chain, the value of center distance was increase by 5*mm* (in practice, it is made physically adjustable between 2 and 5*mm*), thus *m* = 24.475, $K = 72.922mm \cong 73mm$ and L =694.22*mm* ≅ 700*mm*. The chain length used for power transmission from one sprocket to another will be 70*cm*.

The Shaft

The critical shafts are those bearing the three food baskets. The diameter of the shafts for the sprockets is already determined as 26mm (for each of the three food baskets) as being equal to the sprocket bore diameter. These shafts are subjected to fluctuating torque and bending moments. Lateral loading is not pronounced. We need to find out if the selected diameter of the shaft (26mm) made from mild steel material will safely carry the load. We also need to take cognizance of the combined shock and fatigue factors.

According to Hall *et al.* [20], the diameter expected of the shaft to bear such load is given as;

$$d_o^3 = \frac{16}{\pi S_s}\sqrt{(K_bM_b)^2 + (K_tM_t)^2} \tag{21}$$

where

$$M_t = \frac{9550 \times P}{rev/min} \qquad Nm \tag{22}$$

and

$$M_b = \sqrt{{M_y}^2 + {M_z}^2} \qquad Nm \tag{23}$$

From Figure 5, M_y is due to the distributed weight of the basket with food item = -3.03 N-m and M_Z due to the chain tension (19.23N) obtained from equation (18) = -1.87 N-m. Also, in accordance to ASME standard, S_s, the allowable stress, is 55N-mm^2 (with no keyway present). For gradually applied load for shaft already rotating, K_b is 1.5 and K_t is 1.0. Power being transmitted, P is 0.07kW (equation 17) at a rotational speed of 50rev/min. Hence M_t = 13.37 Nm (13370N-mm) and M_b = 3.56Nm (3560N-mm)

Bearing Selection: Rated loads and life of the bearings are the two basic factors commonly considered in any bearing selection. According to Spotts *et al.* [21], load on ball bearing (B_L) (which is what we intend to use) is determined using equation (24).

$$P_B = \frac{B_L}{\pi(R_2-r_1)(R_2+r_1)} \tag{24}$$

and, $B_L = W + W_s + W_F$ (25)

The outer and inner diameters of the ball bearing are 20mm and 16mm respectively as selected and length of the shaft, $L_s = W_{RC} + 2t_{\text{insulation thickness}} + 2t_{\text{sprocket thickness}}$ = 0.66m

$W_s = mg = \rho\left(\frac{1}{3}\pi r^2 L_s\right).g = 8.53\text{N}$ and W_F = 23.1N. ρ is assumed to be 7800kg/m^3 [10].

(These values are for maximum quantity of either maize or yam or plantain that can be loaded into the roasting basket at a time; maize = 2.9kg, yam slices = 3kg and plantain = 1.16kg).

From equation (18) and (25), B_L= 50.86N and from equation (24), P_B = 0.353 N/mm^2

Also, the force to overcome friction [21]; F_T is given as

$$F_T = \frac{2}{3}\pi\mu P(R_2^3 - r_1^3) \tag{26}$$

The calculated design parameters (from equations 1 to 26) are shown in Table 1 with remarks. These values were used for the constructed multipurpose food roaster presented in this work.

3. PERFORMANCE EVALUATION

3.1. Roasting Procedures

Fresh harvested and matured maize, ripe plantain and yam were obtained from Samaru Market, Zaria, Kaduna State, Nigeria. The roaster was used to roast 10 maize cobs of average weight of 3.0kg, 10 peeled plantain fingers of 1.2kg and 10 yam slices of 1.62kg as initial weights before roasting. Then, each item was roasted using roasting temperature range of 160^{0}C-240^{0}C, roasting time of 10-50mins and roasting height (from the electric heating element) of50-150mm.Mass of each food were verified after roasting to ascertain percentage moisture loss using equation (27) given by [22].

$$M_w = \frac{m_2 - m_1}{m_2} \times 100\ (\%) \qquad (27)$$

3.2. Efficiency of the Roaster

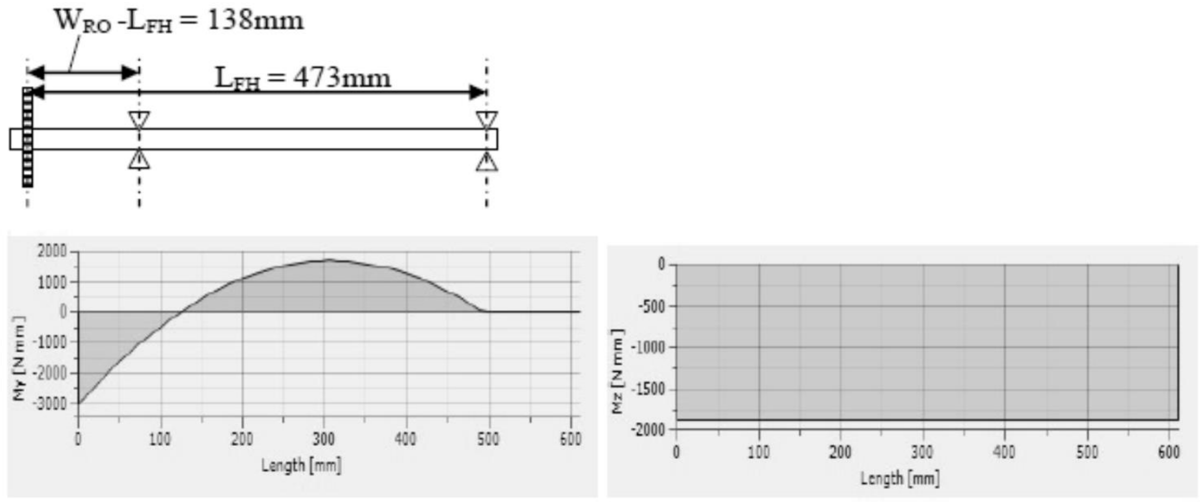
Roasting efficiency based on percentage moisture evaporated from roasted food was verified using equation (28). The efficiency of the roaster is considered at optimal roasting parameters for each food.

$$E_r = \frac{M_w - L}{E_{HC} \times E_F} \qquad (28)$$

4. RESULTS AND DISCUSSIONS

The designed multi-purpose food roaster was fabricated and assembled as shown in Figure 1. The experiments were carried out on maize cobs, sliced yam and plantain of initial average weights of 2.9kg, 3kg and 1.16kg at optimal roasting conditions of 160^{0}C, 11min and 150mm, 186^{0}C, 38min and 149mm, and 220^{0}C, 36min and 138mm for maize cobs, yam slices and plantain respectively. The optimum conditions (shown in figures 6, 7 and8) were arrived at using response surface methodology (RSM) using Design Expert® Software. The experimental data were the range of data (e.g. roasting temperature range of 160^{o}C to 240^{o}C) input into the software.

For maize, the percentage moisture loss was calculated as 6.90% and its roasting efficiency as 68.4%. For the sliced yam it was 6.67% and with a roasting efficiency of 66.1%. For the plantain, the percentage moisture loss is 9.48% and roasting efficiency of 94.11%. Compared to the existing traditional food roaster, which took 21 minutes roasting time with 60%, 46minutes roasting time with 65% and 35minutes roasting time with 63% [8]. In addition, Adisa [23] and Ezekiel *et al.* [6] took 21.16 minutes and 32 minutes to roast 10 fingers of plantain at 185^{0}C and 200^{0}C respectively while 12 minutes and 20 minutes were used by Olainka and Adegboye[9] to roast 10 maize cobs and 10 fingers of plantain. These results shows that there is a significant improvement on the performance of the developed multipurpose food roaster over the traditional and existing food roasting machine because important roasting conditions to predict best roasting qualities were considered in the design and experiment which were absent from the existing design used in comparison.



Maximum: M_y -3030.72 N-mm = -3.03 N-m   Maximum: M_z -1869.730 N-mm = -1.87 N-m

Fig. 2: Bending Moment Diagram

Table 1 – The design parameters as used for the multipurpose food roaster

Parameter	Remark
D_{FH} = 170mm	D_{mv} = 44mm, R_c = 36mm and clearance =of 5mm
L_{FH} = 473mm	
W_{RC} = 611mm	Width clearance of the roaster is 54mm at each end and optimal thickness of insulation is 0.015m (15mm)
L_{RC}=740mm	Distance in between food baskets is 50mm
H_{RC} = 402mm	Maximum roasting distance =150mm, upper clearance = 52 mm
V_{RO} = 0.182m^3	
V_{DH}=0.003m^3	For 6 holes
V_R=0.026m^3	
E_F = 45.6J	Maximum roasting time= 50 minutes, E_E and E_M = 50% each (the name plate specification for the fan selected is 12cm diameter blade, 210m^3/h flow, 220V, 50Hz-AC, 2,300rpm, 0.22m^2 area, 38W).
V_f = 0.00226m^3	V_1 = 0.00072m^3 for 4 pieces, V_2 = 0.00100m^3 for 6 pieces and V_3 =0.00054m^{3}for 4 pieces
m = 17.63kg	Using ρ of 7,800kg/m^3 (according to [10]),
H = 10.21mm.	D_{mh} = 37.7 according to [17]
D_o= 101.31mm	for T_1 =32
= 52.98mm	for T_2 =16
V_{L1} = 10.7m/s	
V_{L2}= 10.5m/s	
P≈ 70W	Power transmitted based on W_B
W = 14.42N	Chain tension (W) on driving side
L = 70cm	The chain length used for power transmission from one sprocket to another
d_o=11mm	M_t = 13.37 Nm, M_b = 3.56Nm
L_s = 0.66m	
B_L= 50.86N	
P_B =0.353 N/mm^2	
F_T =866.01kN	(with μ = 0.3 for steel [21]), this is the minimum rating for the bearing to be used

5. CONCLUSION

A multi-purpose roasting machine presented in this work has been designed and built in accordance to the design specifications. It was evaluated and the result of the evaluation compared well with other researchers results. Maize roasting is 68.4% efficient, Yam, 66.1% efficient and Plantain had a roasting efficiency of 94.11%.

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