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Empirical Design of a Batch Scale Convective Dryer for Sliced Plantain Fruits Using Sawdust-Based Furnace

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ABSTRACT
This paper is focused on the empirical design of a convective hot-air dryer which have 50 kg capacity for drying sliced plantain fruits. This dryer is aided by a sawdust furnace and an air blower which helps supplies the heat. Prior to actual design, pilot scale investigations helped to determine data on drying characteristics for sliced plantain fruits, which include the moisture content, drying time and appropriate drying conditions (45 ^oC, 2 m/s and 60 ^oC, 3 m/s). In the same vein, operating conditions for sawdust combustion were also obtained by experiment. In addition, psychrometric properties of air-water vapor system, and physical-thermal properties of plantain fruits and sawdust were also collected from literature. Empirical correlations were used to obtain appropriate design parameters and specifications for the dryer. These include dryer chamber capacity of 88495.6 cm^3 (with dimensions: 40x40x55.3 cm); sawdust furnace combustion efficiency, heat duty and heat transfer area which were respectively 99.4 %, 220.5 kJ/s and 970 cm^2. The air blower properties were also estimated as follows: airflow=18.84 m^3/min, blower speed=4138.7 rpm, static pressure=0.79 kPa and power capacity=0.52 kW. Thus, based on strong reliance on pilot investigations and empirical evaluations, this convective hot-air dryer design is recommended to be of high integrity.

KEYWORDS: *Sliced plantain fruit, sawdust furnace, convective dryer design, moisture content, and moisture removed.*

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I. INTRODUCTION

A dryer is a mass transfer device often used in process and allied industries to expel moisture (or solvent) from a material (usually in solid or semi-solid or liquid form) to such a level that will cause a balance with the ambient air without compromising the material physical and chemical state, and for which thermal energy is the driving force (Torres et al, 2012). More so, dryers are normally equipped with facilities to enable it create appropriate conditions for the drying operation. Dryers can be used (amongst other purposes) for drying and preserving agricultural produce such as grain, tuber, spice, fruit and vegetable.

The general operating mechanism of a dryer is that of simultaneous heat and mass transfer operation, which requires heat to be deployed into the dryer chamber (where materials to be dried are kept) by either convective or radiant heat transfer method, while moisture (or solvent) in the material is moved to it surface by an internal movement mechanism such as capillary flow and diffusion, and would detach from the material surface into the chamber air stream by evaporation (Rafiee et al., 2007). The air-vapor mixture in the dryer would be released into the surrounding air-environment through a vent or exhaust unit.

Appropriate design considerations for convective dryers, requires defining: material for construction, optimum drying condition of the wet solid, size of dryer chamber (area or volume), quantity of air required for drying, volume of moisture removed from wet solid, heat duty of furnace, air-blower capacity (if any) and other specifications. To evaluate these parameters, mass and heat transport analysis, fan/blower performance and psychrometric analysis would be carried out. Available sources of heat energy for the dryer operation are normally fossil fuels, biomass materials, solar radiation and electric heater (Stroem et al. (2009); Akintunde et al, 2011; Uyigue and Achadu, 2018).

Reports on the performance evaluation, design and fabrication of convective hot-air dryers are widely evident in literature. Some of the notable ones are presented: Bello and Adegbulugbe (2010) compared the energy releasing potentials of three biomass fuels: charcoal, sawdust and rice-husk in a furnace-dryer, set at operating mean-temperatures between 30 and 90 ^{o}C. The heat energy releasing rates for charcoal, sawdust and rice-husk were estimated to be 4.08, 3.56 and 2.93 kJ/min respectively, while the overall thermal efficiency of the furnace-dryer for all fuels was 59 %. Consequently, charcoal was recommended as a faster and cleaner heating fuel compared to the others.

Olanrewaju and Abidemi (2017), also, measured the drying characteristics, proximate composition and thermal properties of two named Nigerian native varieties of unripe plantain fruits (bambam and agbagba) using hot-air oven dryer, tray dryer and fluidized bed dryer at 70 ^{o}C, for drying experiments in which moisture contents were measured. The results obtained showed fluidized bed dryer as a more efficient dryer, because it gave the highest drying rate at lowest drying time of 120 mins.

Al-Busoul (2017), reported an empirical design of a novel-type natural convection solar dryer for drying 100 kg per batch of sliced apple fruits in the Jordanian area. The design calculations took into account an ambient air-temperature and relative humidity for the area as 32 ^{o}C and 45 %, while mass and heat transfer simulation techniques were used for estimating drying and heat transfer rates. The results from the drying simulation envisaged a reduction in the original moisture content of dried apple fruits to 10 % within two days. Other design parameters estimated include solar collector area (18.9 m^2), total useful energy for drying (255.3 MJ) and quantity of water removed from dried apple (83.2 kg water).

Bola et al. (2013), designed and developed an in-bin maize grain dryer of 100 kg batch capacity using electrical heater as source of heat. The operating conditions for dryer were fixed at ambient air temperature, 32 ^{o}C; safe dryer temperature, 43 ^{o}C and ambient relative humidity, 35 %. Mass and heat transfer analysis were used to determine the grain drying curves and heat requirements. Actual dryer design considerations gives dryer chamber volume =154,200 cm^3, moisture removed from grain = 25.29 kg, air required for drying = 1,045 kg, heat required for drying = 31,888.50 KJ and air blower power capacity = 2 hp.

Dhanushkodil et al. (2015), also, designed and constructed a small scale wood-biomass dryer for drying 70 kg batch capacity of cashew nut. Basic components of the dryer include biomass heater, air blower and drying chamber. Dryer air temperature was fixed at 70–75 ^{o}C, while quantity of wood fed to heater and air blower speed were controlled. The dryer chamber size was estimated at 137,500 cm^3. Performance analysis of the dryer with cashew nut showed moisture reduction from 9 to 4 % within 7 h of drying.

The focus of this paper is on the design of a convective dryer for preserving plantain fruits (Musa specie), using sawdust-based biomass heater and air blower as support facilities. This is because plantain fruit is an agricultural produce that is characterized with huge post-harvest loss due to its poor shelf-life, often caused by nature and other agents (like insect, bird, mold etc.) (Osunde, 2008; Dje et al, 2010). Therefore, the drying and processing of plantain fruit into flour or flakes, with appropriate packaging and storage condition can increase its shelf-life to a reasonable extent (Tchango et al, 1999), hence, there is the need for the dryer design.

II. MATERIALS AND METHOD

2.1 Materials

The main materials used for this work are basically plantain fruit (Musa specie) and sawdust which were obtained from the locality. The plantain fruits were washed, peeled and cut into thin slices of regular circular shapes. Also, sawdust samples were separately dried in an oven to moisture contents of 15 and 20 % (dry basis), while its particle size was further reduced by grinding and screening to <400 μm (Figure 1). List of equipment used for this study include laboratory scale hot-air tray dryer (model JAS-TD-12, supported with rotameter and thermocouple), electric weighing balance (model WTD-2000), laboratory scale impactor (model AN-200, with cascaded mesh), densitometer, stop watch (model Samsung A-20), and sawdust packed-based furnace.

(a) (b)

Figure 1: Pilot scale investigations: (a). grinded sawdust samples (< 400 μm) for combustion experiment, (b). sliced plantain fruits undergoing drying.

2.2 Methodology

The methods adopted for this work are experimental and empirical calculations,

2.2.1 Pilot drying experiment

A laboratory hot-air tray dryer, equipped with a rotameter and thermocouple was the equipment used for the pilot drying experiment. Slices of plantain fruits in circular shapes of varied thicknesses: 20, 40 and 60 mm, were separately placed in sample plates which weighed 56, 93 and 154 g, respectively. These sample plates were labeled A, B and C. The operating conditions for drying were set at air temperature: 45 and 60 ^{0}C and air velocity: 2 and 3 m/s. At these drying conditions, the sample plates were placed in the dryer, while monitoring the reduction in weight of the sliced plantain fruits at regular intervals of 10 mins (initially) and 20 mins (towards end of drying) until constant weight of drying was detected. Further drying continued until bone-dry weights of the sliced plantain fruits samples were obtained. This procedure was repeated for all samples of sliced plantain fruits, and for the different drying conditions. Raw drying data in the form of weights of sliced plantain fruits at corresponding drying times were recorded for all the drying runs.

2.2.2 Drying parameter evaluation

(A). Moisture content

Moisture contents of the sliced plantain fruits were empirically estimated on dry basis from the raw drying data obtained from experiment.

✓ **Initial moisture content (M_o):** A ratio of the overall weight of moisture contained in the sliced plantain fruits sample to its bone-dry weight. It is estimated based on eq. 1.

$$M_o = \frac{W_o - W_d}{W_d} \quad (g \ moistrure \ / g \ dry - solid) \qquad (1)$$

Where, W_o = initial weight of sliced plantain fruit sample, g and W_d = bone-dry weight of sliced plantain fruits sample, g.

✓ **Instantaneous moisture content (M_i):** A ratio of weight of moisture contained in the sliced plantain fruits sample (undergoing drying) at any given time to its bone-dry weight. It is also calculated based on eq. 2.

$$M_i = \frac{W_i - W_d}{W_d} \quad (g \ moisture \ / g \ dry - solid) \qquad (2)$$

Where, W_i = instantaneous weight of sliced plantain fruits sample undergoing drying, g.

✓ **Equilibrium moisture content (M_e):** A ratio of constant weight moisture in sliced plantain fruits sample (at any giving time) during drying to that of its bone-dry weight. It is calculated using eq.3.

$$M_e = \frac{W - W_d}{W_d} \quad (g \ moisture \ / g \ dry - soild) \qquad (3)$$

Where, W = constant weight of sliced plantain fruits sample that is undergoing drying, g.

2.2.3 Sawdust combustion trial experiment

Combustion trial experiment for sawdust (biomass) was carried out in a packed-bed furnace which was improvised with a 0.004 m^3 cylindrical can (D = 16 cm, H = 18 cm), closed in both ends. To prevent heat losses, the interior wall of the can was lined with thin-layer refractory cement 10 mm thickness. From the top, the can was filled with dried sawdust (of 524 g) to a bed height of 14 cm. The base of the furnace had an inlet duct for inserting wood fragments that would ignite (in ambient air) to initiate combustion, while the outlet duct at the top served as vent. The top of the furnace also had a perforated lid which allowed natural convection air (at ambient conditions) into the furnace to support combustion.

Pre-combustion conditions for the sawdust packed-bed furnace were set at ambient conditions: air temperature = 25 ^{o}C, air speed = 1 m/s and excess air = 200 %. Ignition proceeded with the firing of wood fragments (in excess of air) at furnace base, while actual combustion was monitored separately for two sawdust samples of same particle size, but at different moisture contents (5 and 10 %) for a period of 85 mins each, during which the following measurements were carried out: average-bed temperature, ash temperature, flue-gas temperature, quantity of sawdust-ash and combustion efficiency.

2.2.4 Measurement of physical and thermal parameters for sawdust and plantain fruit

The basic physical parameter measured by experiment for both sawdust and plantain fruit was density, while values of heat capacities for sawdust and plantain fruit (under similar condition) were obtained from literature.

(A). Density of sawdust

At laboratory condition of 25 ^oC and 1 atm, a 100 ml measuring cylinder was first weighed empty, and was then weighed again after it was filled with dried sawdust of sample size less than 400 µm. The actual volume of sawdust (V_s) was measured after several taps on the measuring cylinder to attain constant height of sawdust. The tap density of sawdust (ρ_s) was then measured using eq. 4. This procedure was repeated twice to find mean density of sawdust.

$$\rho_s = \frac{W_{s2} - W_{s1}}{V_s} \qquad (4)$$

Where, W_{s1} = weight of empty measuring cylinder, g; W_{s2} = weight of measuring cylinder + sawdust sample, g.

(B) Density of plantain fruit

The density of plantain fruit was also measured using a Togoseiki densitometer having water as its immersion fluid. This equipment worked with the principle of Archimedes, in which the operating equation for density measurement is given in eq. 5.

$$\rho_{pf} = \frac{W_{pf} \ x \ \rho_{if} \ x \ instrument \ \ constant}{W^I_{pf}} \qquad (5)$$

Mean density of plantain fruit was obtained from repeated measurements. Where, ρ_{pf} = density of plantain fruit, kg/m^3; ρ_{if} = density of immersion fluid, kg/m^3; W_{pf} = weight of plantain fruit in air, g; W^I_{pf} = weight of plantain fruit in immersion fluid (or water), g.

2.2.5 Estimation of design parameters for the convective hot-air dryer for plantain fruit.

This section covers the estimation of the following parameters: mass of moisture removed from plantain fruit (W_{mr}), quantity of air required for drying (W_{air}), thermal property estimation, size of dryer chamber and air blower parameters.

(A). Mass of moisture removed from sliced plantain fruits (W_{mr})

This parameter represents the amount of moisture to be removed in every batch of sliced plantain fruits being dried in this proposed dryer design. It is estimated based on eq. 6.

$$W_{mr} = W\left[\frac{M_i - M_f}{1 - M_f}\right] \qquad (6)$$

Where, W= batch capacity of dryer (or mass of sliced plantain fruits proposed for drying per run), kg/batch; M_i=mean initial moisture content, g/g-solid; M_f =mean final moisture content, g/g-solid.

(B). Quantity of air required for drying (W_{air})

The mass of air required in the dryer to effect drying of sliced plantain fruits does not change with dryer's position or shape. It is estimated based on eq. 7.

$$W_{air} = \left[\frac{W_{mr}}{Y_2 - Y_1}\right] \qquad (7)$$

Where, Y_2, Y_1 = final and initial absolute humidity of air in the dryer chamber, kg/kg-dry air. Note that Y_2 and Y_1 can be obtained from psychrometric chart based on ambient and dew point temperatures of air in the dryer chamber.

Also, the equivalent volume of air (V_{air}) required to effect drying in the dryer chamber can be measured as ratio of mass of air required for drying to its density, as shown in eq. 8.

$$V_{air} = \frac{W_{air}}{\rho_{air}} \quad (8)$$

Where, ρ_{air} = density of air, kg/m^3.
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(C). Thermal property estimation
Thermo-physical parameters obtained from both experiment and literature were also used in these evaluations.
(i). Heat duty of sawdust-furnace (Q_D) and combustion efficiency (η_c)
This is the amount of heat energy transferred from sawdust-furnace to the contact drying air being blown into the dryer chamber. In other word, it is the difference between the input energy by ignited sawdust and that of the products of sawdust combustion (such as ash, steam and flue gases) as shown in eq. 9.

$$Q_D = \left[W_w \lambda_v + W_{ash} C_{ash} (T_{ash} - T_{ref}) + W_{flue} C_{flue} (T_{flue} - T_{ref})\right] - W_s C_s (T_{ignition} - T_{ref}) \quad (9)$$

Where, Q_D = Heat duty of burner; kJ: W_w, W_{ash}, W_{flue} and W_s = masses of steam, ash, flue gases and sawdust, kg; T_{ash}, T_{flue}, $T_{ignition}$, T_{ref} = temperatures of ash, flue gases, ignition and reference (or surrounding), ^oC; λ_v=latent heat of vaporization, kJ/kg; C_{ash}, C_{flue} and C_s = specific heat capacities for ash, flue gases and sawdust, kJ/kg-K.

The area of heat transfer surface, A_s for the sawdust-furnace is also estimated using eq. 10 as shown,

$$A_s = \frac{Q_D}{U \Delta T_m} = \frac{Q_D}{fU \Delta T_{lm}} \quad (10)$$

Note: for countercurrent heat exchange, $\Delta T_m = \Delta T_{lm}$.
Also, overall heat transfer coefficient, U (W/m^{2}K) for the sawdust-furnace is defined in eq. 11(a) as,

$$U = \frac{1}{\left[2L/K_s + 2t/K_{cs} + 1/h_{air}\right]} \quad (11a)$$

Where, ΔT_m= mean temperature difference, ^oC; ΔT_{lm}= log mean temperature difference, ^oC, f = correction factor, K_s and K_{cs} = thermal conductivities for sawdust and carbon steel, W/m-K, h_{air} = convective heat transfer coefficient for air, W/m2-K, L and t = thicknesses of sawdust bed and carbon steel, m.

Also, the combustion efficiency of the sawdust furnace was measured as a percentage of the ratio of furnace heat duty (Q_D) to energy potential of sawdust:

$$Combustion \ efficiency, \eta_c = \frac{Q_D}{Energy \ potential \ of \ sawdust} \ x \ \frac{100}{1} \quad (11b)$$

(ii). Actual heat supplied to dryer chamber (Q_{actual})
This is the actual quantity of heat supplied to the dryer chamber by the heated air to effect the drying of sliced plantain fruit is given in eq. 12 as,

$$Q_{actual} = W_{mr} C_{air} \Delta T = W_{mr} C_{air} (T_{cin} - T_{ref}) \quad (12)$$

Where, W_{mr} = mass of moisture removed during drying, kg; C_{air}= specific heat capacity of air, kJ/kg K; ΔT = temperature difference in the dryer chamber, ^oC; T_{cin} = chamber inlet temperature, ^oC.

(iii). Effective heat required for drying sliced plantain fruits ($Q_{effective}$)
The quantity of heat required for effecting drying of sliced plantain fruits in the chamber is estimated as shown in eq. 13.

$$Q_{effective} = W_p C_{pf} (T_{cin} - T_{cout}) + W_{mr} \lambda_v \quad (13)$$

Where, W_p= mass of sliced plantain fruit, kg; C_{pf} = specific heat capacity of plantain fruit, kJ/kg K; T_{cout} = chamber outlet temperature, ^oC;

(D). Estimation of size of dryer chamber
For a square shape dryer chamber, the volume will be estimated by dividing the batch weight of sliced plantain fruit (W_b) by its density (ρ_{pf}), using eq. 14.

$$V_{DC} = \frac{W_b}{\rho_{pf}} \quad (14)$$

Where, V_{DC} = volume of dryer chamber, m^3. Since, the height of dryer chamber (H_{DC}) equals its width (W_{DC}) and length (L_{DC}), then, one can use eqs. (15) and (16).

$$V_{DC} = (H_{DC})^3 \quad (15)$$

and

$$H_{DC} = L_{DC} = W_{DC} = (V_{DC})^{1/3} \quad (16)$$

(E). Air blower selection and specifications

A centrifugal blower/fan (forward-curved type, Figure 2) was selected for use in the proposed dryer design based on cost, performance and eases of maintenance, and would be used for blowing heated air via the connecting pipe, passing through the furnace into the dryer chamber. From fan performance chart (GFC, 2005), operating parameters (such as blower speed (N, rpm), blower diameter (D, m), airflow (q, m^3/s), static pressure (P, kPa), air density (ρ, kg/m^3) and power capacity (PC, kW)) were obtained for a referred blower, while fan law-3 (eqs.17 – 19) was used for extrapolating the characteristics of the desired blower being required for the proposed dryer.

$$N_2 = N_1 \left(\frac{D_1}{D_2}\right)^3 \left(\frac{q_2}{q_1}\right) \quad (17)$$

$$P_2 = P_1 \left(\frac{D_1}{D_2}\right)^4 \left(\frac{q_2}{q_1}\right)^2 \left(\frac{\rho_2}{\rho_1}\right) \quad (18)$$

$$PC_2 = PC_1 \left(\frac{D_1}{D_2}\right)^4 \left(\frac{q_2}{q_1}\right)^3 \left(\frac{\rho_2}{\rho_1}\right) \quad (19)$$

Therefore, focus was on predicting the effect of changing airflow (q, m^3/min), density (ρ, kg/m^3) and blower diameter (D, m) on the blower speed (N, rpm), static pressure (P, kPa) and power capacity (PC, kW) of the selected (or desired) blower for the dryer design.

The operating parameters for the referred blower was obtained from performance chart (GFC, 2005) and standard atmosphere table (ICAO, 1993). At given blower speed on the chart, values of operating parameters for referred blower were read at the intersection point between blower and system curves. Thus, parameters of the referred blower are given: N_1 = 1350 rpm, q_1 = 70 m^3/min. (or 4200 m^3/h), P_1 = 0.45 kPa, PC_1 = 1.1 kW and D_1 = 0.45m, including air density at standard condition (ρ_1 = 1.294 kg/m^3).

For the desired blower, air density at normal atmospheric condition is ρ_2 = 1.225 kg/m^3 (ICAO, 1993), while the blower diameter, D_2 and air velocity, V_2 were fixed at 0.2 m and 10 m/s respectively. The airflow, q_2 for the desired blower was estimated using eq. 20 and 21.

$$A_2 = \frac{\pi (D_2)^2}{4} \quad (20)$$

and

$$q_2 = A_2 V_2 \quad (21)$$

Where, A_2 = area of blower, m^2. For the desired blower, the operating parameters (N_2, P_2 and PC_2) were estimated using eqs. 17 – 19.

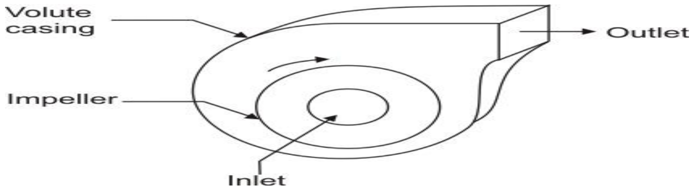

Figure 2: A blower/fan (Forward-curved type)

2.2.6 Selection of materials for dryer construction and layout

(A) Materials selection

Materials selection for the construction of components of the dryer relied on factors such as operating pressure and temperature, corrosion resistance, strength and insulation requirements. Stainless-steel materials would be required for the construction of dryer chamber and trays, because of its strength and high resistance to corrosion. Low carbon-mild-steel materials is also required for constructing frames, angle bars, wedges, nuts and bolts for dryer chamber stability and completeness. Medium carbon-steel materials would be required for the construction of sawdust-furnace casing, while the interior part would be lined with refractory cement to prevent heat loss.

(B). Dryer layout

The dryer in focus is a batch scale convective-type dryer, assisted by sawdust-furnace and air blower. It is aimed at drying 50 kg batch of sliced plantain fruits. The pictorial details are shown in Figures 3 and 4. The dryer chamber is rectangular with a square shape base, which is demarcated with movable perforated trays. The fan blows air through the connecting tube channeled through the sawdust-furnace, and discharges into the dryer chamber. The air being blown through the connecting tube carry's convective heat from the sawdust-furnace into the dryer chamber in order to effect drying.

Ancillary devices which support the drying operations include the dryer chamber exhaust unit, which removes moist air from the dryer; thermometers which measures the air temperatures at the inlet and outlet of dryer chamber as well as that of the sawdust-furnace. The rotameter measures the volumetric flow rate of air being blown into the dryer chamber, while the thermostat attached to the blower controls hot-air inflow into the dryer by sensing and controlling air temperature at dryer chamber inlet.

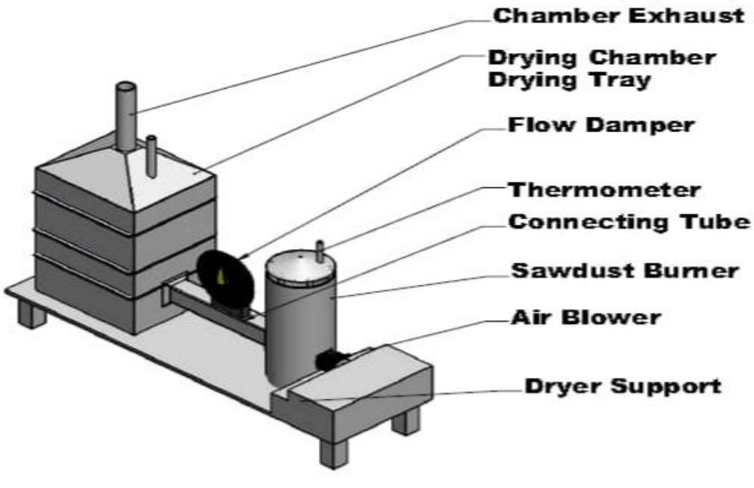

Figure 3: Layout of the convective dryer design

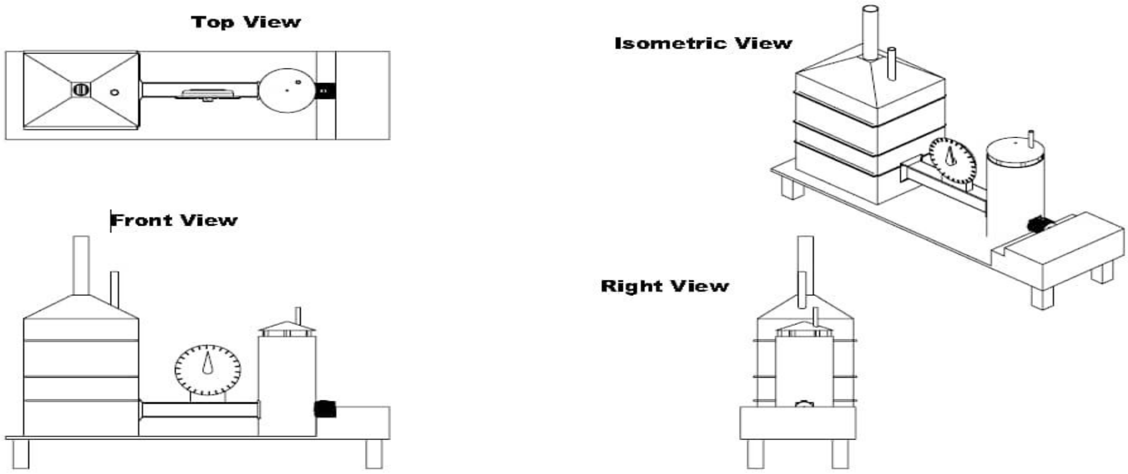

Figure 4: Different views for the convective dryer design.

III. DISCUSSION OF RESULTS

The results obtained from this work are presented in Tables and Figures. Tables 1 and 2 showed the basic properties of plantain fruit and sawdust respectively. Table 3 showed the operating conditions for the proposed dryer design, while Table 4 showed the calculated design parameters for the dryer. Also, Figures 5 - 7 showed the drying characteristics of the sliced plantain fruit. These results were discussed under the following sub-headings: (1). Drying characteristics of sliced plantain fruit, (2). Energy potential of sawdust furnace, (3). Empirical evaluation of the dryer design.

3.1 Drying characteristics of sliced plantain fruit

A pilot (or pre-design) drying experiment conducted for sliced plantain fruits of average mass of 101 g at different operating air temperatures (45 and 60 ^{0}C) and air velocity (2 and 3 m/s), showed an average initial and final moisture contents of 1.132 and 0.005 g/g-solid respectively for sliced plantain fruit which amounts to 99.6 % moisture removal (Table 1).

Table 1: Basic properties of plantain fruit

S/N	Parameter	Value
1	Mean density of plantain fruit, ρ_{pf}	565 kg/m^3
2	Quantity of plantain fruit dried per batch, W	50 kg batch
3	Moisture content of sliced plantain fruit (dry basis): a) Mean initial moisture content of plantain, M_i b) Mean final moisture content, M_f	 1.132 g/g-solid 0.005 g/g-solid
4	Thermal properties of plantain fruit, pf: a) Specific heat capacity, C_{pf} b) Thermal conductivity, k_{pf} c) Latent heat of water vaporization , λ_v (Olarenwaju and Abidemi, 2017)	 1.685 kJ/kg-k 0.257 J/s-m-k 2265 kJ/kg

From the drying data (Figures 5 – 7), the sliced plantain fruits showed continuous reduction in moisture content within the drying time for all the drying runs (which ranged between 120 and 180 mins). It was also observed that the drying time was dependent on the thickness of the plantain slices, hence, drying time increased with increasing thickness of the sliced plantain fruits. The trends of the drying curves for the different drying run showed falling rate regimes whose curves terminated at very low moisture contents.

Also, the operating air temperature and air velocity of 60 ^{o}C and 3 m/s respectively, showed a more efficient drying condition for the sliced plantain fruits irrespective of its thickness, in which the average final moisture content was less than 0.001 g/g-solid. These results corroborated with Olanrewaju and Abidemi (2017) in which a similar operating air temperature and drying time of dryer (70 ^{o}C, 120 mins.) gave the most efficient drying for plantain fruit.

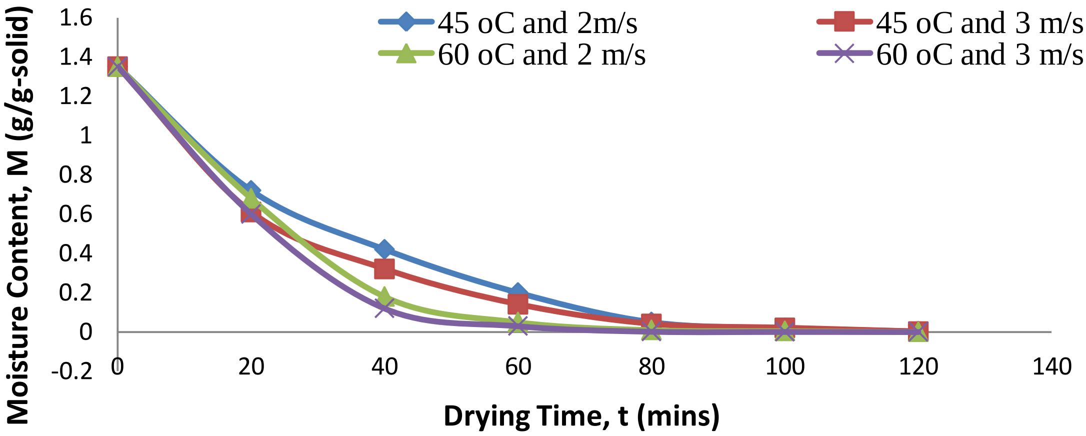

Figure 5: Graph of moisture content versus drying time for sliced plantain fruits of 20 mm thickness at different air temperature and air velocity

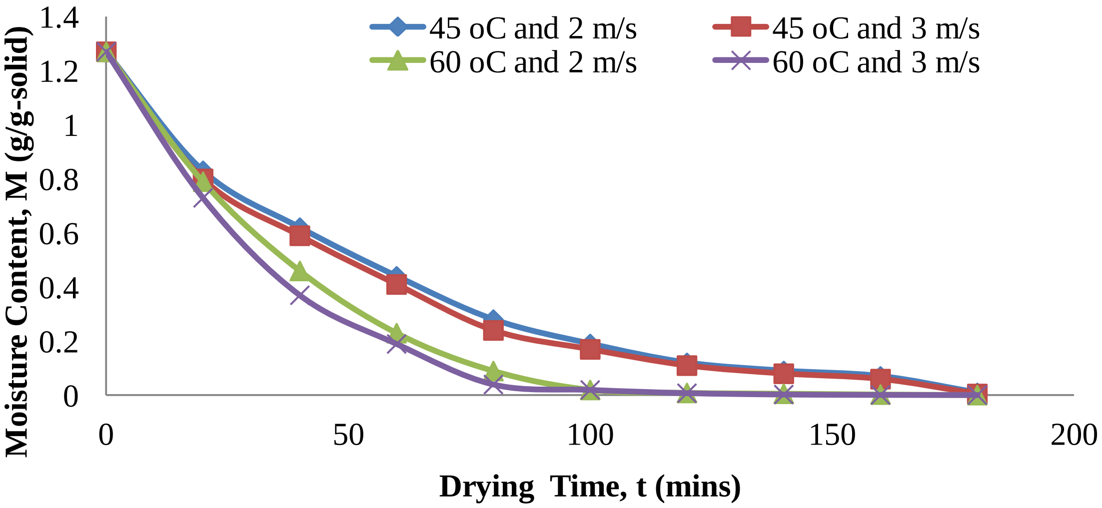

Figure 6: Graph of moisture content versus drying time for sliced plantain fruits of 40 mm thickness at different air temperature and air velocity

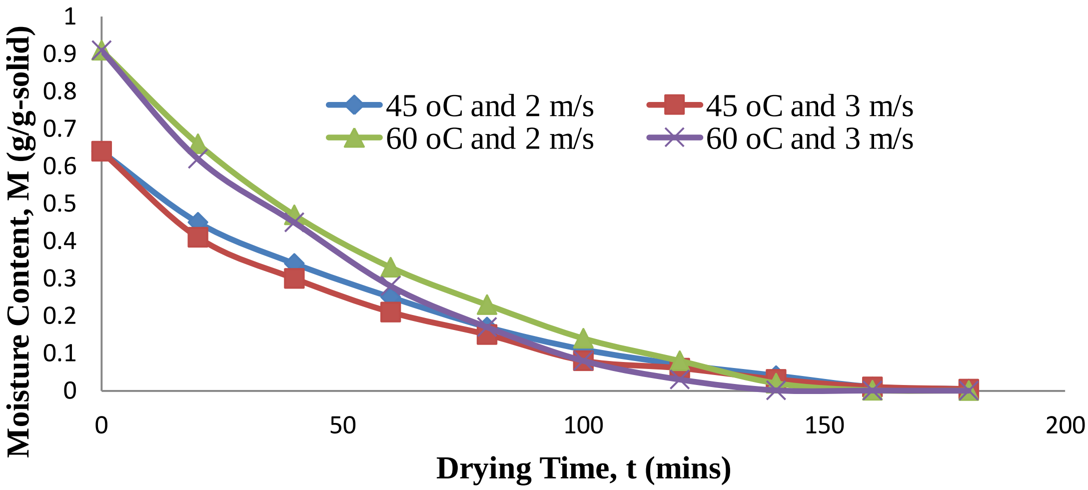

Figure 7: Graph of moisture content versus drying time for sliced plantain fruits of 60 mm thickness at different air temperature and air velocity.

3.2 Energy release potential of sawdust

Prior to actual design of the dryer, energy release-potential of sawdust was measured experimentally through an improvised muffle furnace (packed with sawdust). The operating conditions for the furnace were measured including other basic properties of sawdust (Tables 3 and 4), the furnace heat duty was estimated at 220.50 kJ/s by combusting 524 g sawdust bed, while actual heat and effective heat requirements for a dryer capacity of 50 kg sliced plantain fruit were estimated at 2021.7 and 129530.7 kJ respectively.

Therefore, to meet with the specification for effective heat requirement for the drying of sliced plantain fruits, reloading operations of furnace with sawdust would be required during actual dryer operation. This finding is also corroborated by the works of Bello and Adegbulugbe (2010) wherein the heat energy releasing potentials of sawdust (amongst other biomass fuels) to support drying operations was estimated at 3.56 kJ/min, which is equivalent to 427.2 kJ of released heat, over a combustion time of 120 mins. A combustion efficiency of 99.4 % (Table 5) for sawdust furnace is an indication of high feasibility of applying sawdust as fuel for sliced plantain drying.

Table 3: Basic properties of sawdust

S/N	Parameter	Value
1	Mean density of sawdust, (Rizki et al, 2010)	790 kg/m^3
2	Particle size distribution (PSD) of sawdust	< 400 µm
3	Moisture content (dry basis): a) Sawdust sample 1 b) Sawdust sample 2	 5 g/g-solid 10 g/g-solid
4	Thermal conductivity of sawdust, K_s (Ilomets et al, 2014)	 0.85 kW/m-k
5	Calorific value of sawdust (Awulu et al., 2018)	3155.3 kcal/kg
6	Specific heat capacity: a) sawdust, C_s b) ashes, C_{ash} c) Flue gases, C_{flue}: ✓ CO_2 ✓ CO (Engineering toolbox, 2003)	 0.9 kJ/kg-k 0.84 kJ/kg-k 0.844 kJ/kg-k 1.02 kJ/kg-k

Table 4: Operating conditions of proposed dryer design

S/N	Parameter	Calculation	Value
1	Air condition in dryer chamber:		
	a) Operating temperature:		
	✓ Dryer chamber inlet, T_{in}		60 ^oC
	✓ Dryer chamber outlet, T_{out}		45 ^oC
	b) Absolute humidity for ambient and dryer inlet temperatures at relative humidity of 100 and 60 % respectively, kg/kg-air:		
	✓ Initial, Y_1, (at 25 ^oC)		0.025
	✓ Final, Y_2, (at 60 ^oC)		0.1
	c) Convective heat transfer coefficient for air, h_{air} (Engineering toolbox, 2003)		36 kW/m^2-k
	d) Specific heat capacity of air at constant pressure, C_{air} (Kyle, 1984)	W_{mr}=50 x (1.132-0.005)/(1-0.005)	1.02 kJ/kg-k
	e) Mass of moisture removed from plantain, W_{mr}, kg	W_{air}=56.63/(0.1-0.025)	56.63 kg
	f) Mass of air required for drying in the chamber, W_{air}	V_{air}=755.11/1.225	755.11 kg
	g) Volume of air required for drying 50 kg batch of sliced plantain fruits, V_{air}		616.41 m^3
2	Sawdust-furnace condition:		
	a) Mass of sawdust, W_s		524 g
	b) Mass of ash, W_{ash}		25.4 g
	c) Average sawdust moisture, M_s		7.5 g/g-solid
	d) Operating temperatures:		
	✓ Ignition, T_{ig}		60 ^oC
	✓ Combustion, T_c		320 ^oC
	✓ Ash, T_{ash}		105 ^oC
	✓ Reference, T_{ref}		25 ^oC
	e) Operating pressure, P		101.3 kPa

3.3 Evaluation of the convective dryer design

This dryer is designed for a batch scale capacity of 50 kg of sliced plantain fruits. The major components of the dryer include: dryer chamber, sawdust furnace, air blower (or fan) and connecting pipe. The dryer chamber is of square base and vertical in orientation. It has a volume capacity of 88,495.6 cm^3 (with dimensions: 40 x 40 x 55.3 cm) (Table 5). This estimate corroborates Bola et al (2013) and Dhanushkodil et al (2015) wherein similar range of results for dryer chamber capacity were also reported. Note also, that the convective heat is supplied to the dryer chamber by the sawdust furnace via the aid of an air blower, which increased the dryer chamber humidity from 0.025 to 0.1 kg/kg-air (Table 4). The furnace has a heat transfer surface area of 970 cm^3, and operates at 99.4 % combustion efficiency (Table 5).

An air blower/fan (forward-curve type) was selected for the dryer design. The diameter (20 cm) and air velocity (10 m/s) of the air blower (or fan) were fixed, while the other blower parameters were estimated (in line with fan law-3) as follows: airflow=18.84 m^3/min, blower speed=4138.7 rpm, static pressure=0.79 kPa, power capacity=0.52 kW (Table 5). The connecting pipe (length, 1.5 m; diameter, 15 mm; thickness, 2 mm) is linked between the blower and dryer chamber, and passes through the furnace. It is the channel for conveying convective heat to the dryer chamber.

Table 5: Estimated design parameter for the proposed dryer

S/N	Parameter	Calculation	Value
1	Sawdust-furnace design: Cylindrical shape and vertical orientation. a) Heat duty, Q_D b) Heat release rate for sawdust (@ 40 mins combustion time), Q^I_D c) Combustion efficiency, η_c d) Overall heat transfer coefficient, U e) Log mean temperature difference, ΔT_{lm} f) Area of heat transfer, A g) Diameter of furnace, D h) Height of Furnace, H, (at H/D = 2.2)	Q_D=(0.0393x(-13434.3+2265)+0.0254x(-32134.4+0.84x80)+0.459x(-1157472.7+1.864x295))-(0.524x(-5907.2+0.9x35)) Q_D/combustion time=529202/(40x60) η_c = Q_D/Energy potential = 529202/(529202 + 3111.88) x 100 U=1/((0.14/0.85)+(0.004/51.5)+(1/36)) ΔT_{lm} =((320-60)-(105-25))/ln(533/353) A=[220.50/(5.19 x 436.84)] x 10000 D=(4 x 970x7/22)$^{1/2}$ H = 2.2 x 35.1	-529202.0 kJ 220.50kJ/s 99.4 % 5.19 kJ/s-m^2-k 436.84 k 970 cm^2 35.1 cm 77.2 cm
2	Heat required for drying, Q, a) Actual heat, Q_{actual} b) Effective heat, $Q_{effective}$	Q_{actual} = 56.63 x 1.02 x (60 - 25) $Q_{effective}$=50 x 1.685 x (60 -45) + 56.63 x 2265	2021.7 kJ 129530.7 kJ
3	Dryer chamber design: square base and vertical orientation a) Volume, V, cm^3 b) Length, L, cm c) Breadth, B, cm d) Height, H, cm	V = (50/565) x 10^6	88495.6 cm^3 40 cm 40 cm 55.3 cm
3	Desired blower (or fan) parameter: a) Fan diameter, D_2 b) Fan area, A_2 c) Airflow, q_2 d) Fan motor speed, N_2 e) Static pressure, P_2 f) Power capacity, PC_2	A_2 = ((22/7) x (0.2)^2)/4 q_2 = 0.0314 x 600 N_2 = (1350)(0.45/0.2)^3 x (18.84/70) P_2 = (0.45) x (0.45/0.2)^4 x (18.84/70)^2 x (1.225/1.294) PC_2 = (1.1) x (0.45/0.2)^4 x (18.84/70)^3 x (1.225/1.294)	0.2 m 0.0314 m^2 18.84 m^3/min 4138.7 rpm 0.79 kPa 0.52 kW
4	Specifications for connecting tube: carbon steel, cs. a) Thermal conductivity of carbon steel, K_{cs}, (Ranjbarnodeh et al, 2011) b) Length, L c) Diameter, D d) Thickness, t		51.5 W/m-k 1.5 m 15 mm 2 mm

IV. CONCLUSION

An empirical design of a convective hot-air dryer for sliced plantain fruits drying which used sawdust furnace as heat source was reported in this paper. Although, this dryer was not physically fabricated, but, in line with data obtained from pilot scale investigations, in addition to actual design evaluations and specifications, which also relied on relevant physical and thermal property data in the literature, there is a strong assurance of high integrity design if fabricated.

REFERENCES

[1]. Akintunde T.T., Akintunde, B.O. and Fagbeja, A. (2011). Effect of blanching methods on drying kinetics of bell pepper, African Journal of Food, Agriculture, Nutrition and Development, 11(7): 5457- 5474.

[2]. Al-Busoul, M. (2017). Design of fruits solar energy dryer under climatic condition in Jordan. Journal of Power and Energy Engineering, 5: 123-137

[3]. Awulu, J.O., Omale, P.A. and Ameh, J.A. (2018). Comparative analysis of calorific values of selected agricultural wastes. Nigerian Journal of Technology, 37(4): 1141–1146.

[4]. Bello, S.R. and Adegbulugbe, T.A. (2010). Comparative study on utilization of charcoal, sawdust and rice husk in biomass furnace-dryer. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Manuscript 1592, 12: 1 – 8.

[5]. Bola F. A., Akande F. B., Ibrahim S. O., Sanusi B. A. (2013): Design Parameters of a Small Batch in Bin Maize Dryer. Agricultural Sciences Journal. Vol 4 (513):90-95.

[6]. Dhanushkodi1, S., Wilson, V.H. and Sudhakar, K. (2015). Design and performance evaluation of biomass dryer for cashew nut processing. Advances in Applied Science Research, 6(8): 101-111.

[7]. Dje, M.K., Dabonne, S., Guehi, S. T. and Kouame, P. L, (2010). Monitoring of some biochemical parameters of two yam species (dioscoreaspp) tube parts during post-harvest storage, Advancejournal of Food Science and Technology, 2(3):178 – 183.

[8]. Engineering ToolBox (2003). Specific heat of solids (online). Available at: https://www.engineeringtoolbox.com/specific-heat-solids-d_154.html (accessed 9 September, 2020).

[9]. Greenheck Fan Corporation, GFC (2005). Fan Application No. FA/100-99. A technical bulletin for engineers, contractors and students in the air movement and control industry. http://www.greenheck.com/info/

[10]. International Civil Aviation Organization, ICAO (1993). Manual of standard atmosphere (extended to 80 km or 262 500 ft). 3rd edition, ICAO Doc 7488-CD.

[11]. Kyle, B.G. (1984). Chemical and process thermodynamics. Englewood Cliffs and Prentice Hall, New Jersey.

[12]. Ilomets, S., Kuusk, K., Paap, L., Arumägi, E. and Kalamees, T. (2014). Impact of linear thermal bridges on thermal transmittance of renovated apartment buildings. Journal of Civil Engineering and Management. (https://www.researchgate.net/publication/303955080).

[13]. Olanrewaju, A.S. and Abidemi, J.O. (2017). Drying characteristics and thermal properties of two local varieties of unripe plantain. American Journal of Science and Technology, 4(5): 74 - 79.

[14]. Osunde, Z.D. (2008). Minimizing post-harvest losses in yam (dioscorea spp): treatments and techniques, International Union of Food Science and Technology, Raleigh: 1 – 12.

[15]. Rafiee, S., A. Jafari, M. Kashaninejad and M. Omid, 2007. Experimental and numerical investigations of moisture diffusion in pistachio nuts during drying with high temperature and low Relative Humidity. *Int. J. Agric. Biol.*, 9: 412–5

[16]. Ranjbarnodeh, E., Serajzadeh, S., Kokabi, A.H. and Fischer, A. (2011). Effect of welding parameters on residual stresses in dissimilar joint of stainless steel to carbon steel. Journal of Material Science, 46: 3225–3232. (https://www.researchgate.net/publication/227144263).

[17]. Stroem, L.K., Desa, D.K., and Hoadley, A.F.A. (2009). An Evaluation of Superheated Steam Drying of Brewer's Spent Grain. Journal of Advanced Powder Technology https://www.researchgate.net/publication/251606760

[18]. Tchango Tchango, J., Bikoï, A., Achard, R., Escalant, J.V. and Ngalani, J.A. (1999). Plantain: Post-harvest operations. Centre de Recherches Regionales sur Bananiers et Plantains, Cameroon (CRBP), Food Agricultural Organization (FAO).

[19]. Torres, R., Montes, E.J., Andrade, R.D., Perez, O.A and Toscano, H. (2012). Drying kinetics of two yam (DioscoreaAlata) varieties, Dyna (Medellin Colombia), 79(171): 175 – 182.

[20]. Uyigue, L. and Achadu, M.A. (2018). Measurement and modeling of the thin layer drying properties of selected varieties of yam assisted by hot-water blanching. International Journal of Engineering and Modern Technology, Vol. 4 No. 1, 35 – 53.

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