Design parameters for a small- scale batch in-bin maize dryer

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ABSTRACT

Early season maize is harvested with high moisture content that makes it impossible to store. The sale of early season maize in green form is uneconomical to the farmer. Experience had shown that farmers could hardly make the cost of production from their sales. Also, grain losses are high when maize is harvested green. To minimize grain losses and thereby increase value and the profit margin of the farmer, a grain dryer is necessary for wet grains. Therefore, this paper presents the design and development of a batch in-bin maize grain dryer. Some properties of maize such as moisture content and bulk density were determined to get information required for design of the dryer. The dimension of drying chamber, amount of moisture to be removed in a batch, quantity of air required to effect drying, volume of air required to effect drying, blower capacity, quantity of heat required to effect drying and actual heat used to effect drying were all designed for. A maize dryer was developed with a batch size of 100 kg of threshed wet maize. The dryer can be used in laboratory for experimental purpose as well as on the farm for commercial purposes. The dryer can be used to measure drying rates of maize at different initial moisture contents, drying air temperatures, drying air velocities and grain beds. The effects of different drying temperature, air velocity, loading and agitating speed on the quality of dried maize can be investigated with the dryer.

Keywords: Design and Development; In-bin Maize dryer; Fresh Maize Grain; Moisture Content; Heat Transfer; Drying Rate

1. INTRODUCTION

Maize is an all-important crop which provides an avenue for making various types of foods. It also has some medicinal values and serves as raw-materials for many industries. Grain is the most important part of maize crop and is put to many uses.

Maize (*Zea mays* L.), or corn, is the most important cereal crop in sub-Saharan Africa and, with rice and wheat, one of the three most important cereal crops in the world. Maize is high yielding, easy to process, readily digested, and relatively cheaper than other cereals. It is also a versatile crop; growing across a range of agro ecological zones. Every part of the maize plant has economic value: the grain, leaves, stalk, tassel, and cob can all be used to produce a large variety of food and non-food products.

Maize grain could be processed into different forms, especially in the form of maize meal, which is an important food for large numbers of people in Africa, providing significant amounts of nutrients, in particular calories and protein. [1] Showed that 22 of 145 developing countries had a maize consumption of more than 100 g per person per day. In a dietary intake survey in South Africa, [2] found that maize meal was consumed by almost, all of the respondents, both males and females, in the rural, farm, informal settlement and middle class urban strata.

In industrialized countries, maize is largely used as livestock feed and as a raw material for industrial products, while in developing countries, it is mainly used for human consumption. In sub-Saharan Africa, maize is a staple food for an estimated 50% of the population. It is an important source of carbohydrate, protein, iron, vitamin B, and minerals. Africans consume maize as a starchy base in a wide variety of porridges, pastes, grits, and beer. Green maize (fresh on the cob) is eaten parched, baked, roasted or boiled; playing an important role in filling the hunger gap after the dry season.

The harvesting of the early season maize in Nigeria is

usually between July and October when the rain is fully established. At this time, natural drying on the field is difficult due to low atmospheric temperature and high relative humidity. If the crop is left on the field to dry, it will continue to deteriorate because of the slow rate of drying. They are therefore harvested with the high moisture content and sold cheaply to be cooked or roasted for consumption. This decrease in farmer's income can be averted, if after harvesting, the maize can be dried and stored.

Drying is one of the oldest methods of food preservation. It is the removal of moisture from an agricultural produce/biomaterial to moisture content in equilibrium with the surrounding air or to such moisture content that can decrease the mould's enzymic action and insects' infestation. Food stuffs are usually dried to enhance their storability, transportability, texture and retainability.

Drying reduces the amount of water contained in the crop after harvest to an acceptable level for marketing, storage or processing [3]. Both grain temperature and moisture content are critical in maintaining quality. Mould and insect activities are greatly reduced below $15°C$ safe moisture levels for storage. However, these depend on grain variety, length of storage, storage structure, and geographical location.

The major input in a drying process is the heat which raises the temperature of the inlet air which is blown through a static grain bulk to be dried. The wet grains can only be dried if the inlet air conditions are drier than the wet grain. This means that the moisture contained in the inlet air can be removed by raising its temperature, thus, increasing its ability to remove moisture from a wet grain. The exit air which leaves the dryer after passing through the wet bulk of grain could accumulate and subsequently condense within the dryer if there are no adequate exit channels and if the airflow rate is low [4]. The cooking of the grains and stress cracking due to the development of high internal grains' temperatures and pressures can be avoided if the condition of the inlet air introduced into the dryer systems is carefully selected. This will ensure the good quality of out-loaded grain bulk. Also, during drying, the conditions of grains nearest to the inlet are always different from those nearest to the outlet and continue along single line within the bulk. These differences may occur as temperature of the air voids between grains and as moisture content of the grain when the progression of the air fronts are not uniformly distributed.

In Nigeria and other African countries, post-harvest losses of agricultural products are very high. This is due to the fact that each of the products has its season and it is mostly produced in excess of what is immediately needed. The losses are due to lack of appropriate preservation and storage facilities. These losses made the products unavailable throughout the year and where they are available there is a sharp difference in prices at harvest and later after harvest. Therefore, the objective of this study is to design and develop a batch in-bin maize grain dryer for freshly harvested maize for on farm usage with a view to reducing the postharvest losses faced by farmers thereby increasing their income.

2. MATERIALS AND METHODS

In order to develop an efficient batch in- bin dryer for maize, the following properties and parameters were determined.

2.1. Determination of Moisture Content

The moisture content of the maize was determined to know the amount of moisture to be removed from the freshly harvested maize. The sample freshly harvest maize grain was weighed and dried in a ventilated electric oven set at $65°C$ for 24 hs when constant weight was obtained in accordance with [5]. The sample was removed and allowed to air-cool. The weight of the dried sample was determined using a digital sensitive weighing balance of 0.01 g accuracy. The moisture content (%) was computed using **Eq.1**.

$$mc = \frac{100(W_1 - W_2)}{W_1} \qquad (1)$$

2.2. Determination of Bulk Density of Maize at Harvest

[6] Developed an empirical formula which relates bulk density and moisture content for maize as stated in **Eq. 2**.

$$TW_m = 0.7019 + 0.01676 M_{wb} - 0.0011598 M_{wb}^2 + 0.00001824\ M_{wb}^3 \qquad (2)$$

Maize harvested at maturity normally has an average moisture content of 32% (wb) [7].

Substituting the value of $Mwb = 32\%$ (wb) into Eq.2 gives.

$TW_m = 0.7019 + 0.01676\ (32) - 0.0011598\ (32)^2 + 0.00001824\ (32)^3$

$TW_m = 0.6483\ g/cm^3$

$TW_m = 648.3\ kg/m^3$

2.3. Design Considerations

In designing the dryer, the following considerations were made:

To have a uniform dried product such that the temperature and moisture content are the same at every levels of the grain thickness, the inlet air would be directed as to span through the entire circular base of the dryer.

To avoid accumulation of vapour, the upper lid of the dryer will be perforated so as to allow easy flow of vapour picked by the heated air from the grains to the atmosphere.

To reduce the static pressure which the fan must overcome in order to supply the desired airflow, an agitator shaft was incorporated. A cylindrical shaped dryer is therefore considered for easy and uniform agitation.

To reduce the heat loss due to conduction and to conserve energy generated by the heaters, the drying cylinder was lagged with glass fiber because of its effectiveness and availability.

To ensure that the grains would not be contaminated, the inner wall, the agitation shaft and the perforated flour of the dryer were made of stainless steel-material and

To ensure that the rate of drying of the grains is enhanced, appropriate size of heater was considered to raise the temperature of the drying air.

2.3.1. Design of the Dryer

The design of the maize dryer (**Figure 1**) was based on the following: amount of moisture to be removed, quantity of air required to effect drying, volume of air to effect drying, blower design and capacity, quantity of heat required, heat transfer, actual heat used to effect drying, rate of mass transfer, thermal efficiency, and the drying rate. The design was based on ambient temperature (T_1) of 32℃; this is applicable for steady flow systems as stated by [8]. The initial humidity ratio (H_{r1}) is determined to be 0.01 kg/kg dry air using the psychometric chart under normal temperature and 101.325 kPa barometric pressure. The safe drying temperatures (T_2) required for drying maize is 43℃ as stated by [9]

2.3.2. Design of the Drying Chambers (Dimension)

The dimension of the drying chamber was determined with the assumptions that, the configuration is cylindrical and mass of maize grain per batch is 100 kg.

The bulk density of the maize grain depict that 6 482 kg of freshly harvested maize occupies 1 m^3 by volume,

1 kg of freshly harvested maize occupies 1/648.2

= 0.001542 m^3

100 kg will occupy 0.001542 × 100 m^3

= 0.1542 m^3

Since the dryer is cylindrical, assuming a diameter of 600 mm

Volume = base area x height.

0.1542 = π × 0.3^2 × height

height = 0.1542/π × 0.3^2

= 0.5453 m.

The dimension of the drying chamber was therefore determined to be 600 mm diameter and 546 mm height.

2.4. Amount of Moisture to be Removed

Amount of moisture to be removed in kg (M_R) is given in **Eq.3** as:

$$M_R = M\left[\frac{Q_1 - Q_2}{1 - Q_2}\right] \tag{3}$$

Where, M is dryer capacity per batch (kg), Q_1 = initial moisture content of the maize to be dried 35%, Q_2 = maximum desired final moisture content, which is 13% based on experimental results [10]. M_R is therefore determined to be 25.29 kg.

2.5. Quantity of air Required to Effect Drying

Quantity of air required to effect drying in kg (Q_a). This can be calculated from **Eq. 4** by [11]

$$Q_a = \left[\frac{M_R}{H_{r2} - H_{r1}}\right] \tag{4}$$

where Hr_1 and Hr_2 are initial and final humidity ratios in kg/kg dry air respectively; and MR is as determined in Eq.3. The average ambient temperature and relative humidity are 31℃ for dry bulb temperature, 28℃ for wet bulb temperature and 35% for relative humidity. The initial humidity ratio Hr_1 is determined to be 0.01 kg/kg dry air using the psychometric chart under normal temperature and 101.325 kPa barometric pressure. After the heat has been supplied, the temperature of the product rises to 50℃ giving the final humidity ratio (Hr_2) as 0.028 kg/kg dry air. Substituting these values of Hr_1 and Hr_2, and Q_1 and Q_2, into **Eq.4** gives the quantity of air required to effect drying (Qa) as 1,405 kg.

2.6. Volume of Air to Effect Drying

Volume of air to effect drying in m^3 (Va) can be determined using Eq.5 by [11]:

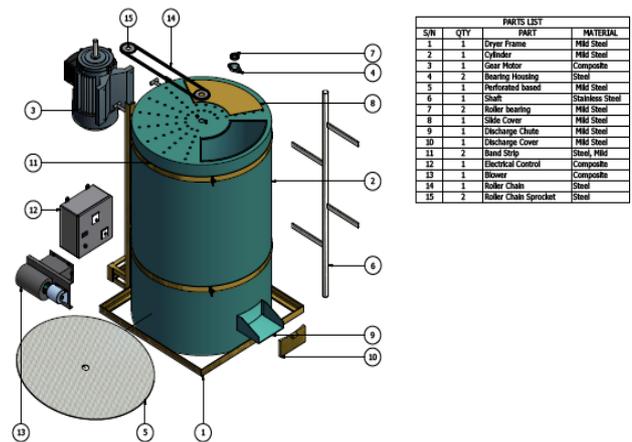$$V_a = \frac{Q_a}{\delta_a} \tag{5}$$

Figure 1. Exploded view of the dryer.

where, δ_a is the density of air in kg/m^3 which is determined at 0℃ to be 1.115 kg/m^3 based on properties of common fluids presented by [12]. The volume of air to effect drying was therefore calculated to be 1,260.10 m^3

2.7. Blower Design and Capacity

The blower serves the purpose of transferring heated air from the heat exchanger to the dryer cabinet. The selection was based on the characteristics of centrifugal fan performance curve based on the **Eqs.6-8**:

$$N_2 = N_1 \left[\frac{q_{1\%}}{H_{1\%}}\right]\left[\frac{H_{2\%}}{q_{2\%}}\right] \tag{6}$$

$$D_2 = D_1 \left[\frac{H_{1\%}}{q_{1\%}}\right]\left[\frac{q_{1\%}}{H_{2\%}}\right] \tag{7}$$

$$hp_2 = hp_1 \left[\frac{D_2{}^5}{D_1{}^5}\right]\left[\frac{N_2{}^3}{N_1{}^3}\right] \tag{8}$$

where N is the speed (rpm) of the electric motor, H is the static pressure (Pa), q is the volumetric flow rate of air (m^3/min), D is the diameter of the blower (m) and hp is the motor horse power. Based on the selection from the chart presented by [13] on the performance curve of a backward-curved centrifugal fan showing system characteristics, N_1 is 1000 rpm, D_1 is 0.46 m, H_1 is 1.41, H_2 is 1.09, q_1 is 226.4 m^3/min, q_2 is 198.1 m^3/min and hp_1 is 2.28. Based on **Eq.6**, N_2 is taken to be in 1000 rpm since an electric motor of 1000 rpm is selected. The value of D_2, (m) is calculated based on Eq. 7 while hp_2 is calculated from Eq. 8 for which a 2hp electric motor is selected.

The Blower Capacity (BC) is calculated from **Eq.9** [14]:

$$BC = Q_a + Q_a(n) \tag{9}$$

where $Qa = Qm + Re + Zk$ and $Qm = \delta_a \times q_2 = 1.115$ kg/m$^3 \times 198.1$ m^3/min = 220.88 kg/min; Re = 25% of Qm which is 55.22 kg/min; Zk = 1-2% of Qm which is 4.42 kg/min at 2%; and n= percentage safety factor that ensures an adequate supply of air in all operating conditions at 15% but usually 10% - 20%. Substituting, BC is therefore calculated to be 322.6 kg/min.

2.8. Quantity of Heat Required for Effective Drying (Hr) in kJ

The quantity of heat required for effective drying is as presented in **Eq.10**

$$H_r = (M_x H_K) + (H_L x M_R) \tag{10}$$

where M = dryer capacity per batch (kg) = 100 kg; $H_k = C_T (T_2-T_1)$, whereas C_T is specific heat of maize = 1.8 kJ/kg℃; and T_2-T_1 = 50 - 32℃, H_L = latent heat of vaporization =1248.1 kJ/kg; and M_R = amount of moisture was removed (kg) substituting these values into **Eq.10**, H_r is calculated to be 31,888.50 kJ.

2.9. Heat Transfer Rate

The heat transfer rate (Qht) can be determined from **Eq.11** by [12] as:

$$Q_{ht} = hA_e T_B \tag{11}$$

where h = heat transfer coefficient = $N_u K/d$ and with Nu (Nusselt) = 121.3 = $0.13_a{}^{0.33}$ with R_a = 109; K as thermal conductivity = 0.0305 kW/mK and d as diameter of the heat exchanger = 0.56 m, the value of h is 6.607 kW/m^2℃; A_e = surface area of the heat exchanger = 0.7389 m^2; and T_B = temperature of hot air in the blower, ℃. The value of heat transfer rate (Q_{ht}) is therefore determined to be kJ.

The quantity of heat that can be lost through the blower in the process is calculated from **Eq.12**

$$qL = KA_b T_{BE/\delta_k} \tag{12}$$

where q_L = quantity of heat lost (kJ); K = thermal conductivity of mild steel = 58

W/m.K; A_b = surface area of the blower = 0.88 m^2; T_{BE} = temperature difference between the hot air in the blower and the environment = T_2-32℃; and δ_k = distance = 1. The value of q_L is therefore calculated in kJ. The net heat transfer rate (Q_{htr}) that will reach the cabinet is (Q_{ht} - q_L) kJ.

2.10. Actual Heat used to Effect Drying (HD)

The quantity of heat used in effecting drying H_D can be determined from Eq. 13

$$H_D = C_a T_c M_R \tag{13}$$

where C_a = specific heat capacity of air = 1.005 kJ/kg℃; M_R = amount of moisture to be removed kg; and T_c = temperature difference in the dryer cabinet = T_2-32℃ =50-32℃. The quantity of heat is therefore calculated to be 457.50 kJ.

3. COMPONENT PARTS OF THE DRYER

The component parts of the dryer are; frame, drying cylinder, agitating shaft, heat exchanger, air blower and electrical control panel. The components were fabricated and assembled according to design. The exploded view of the dryer is show in **Figure 1**.

The dryer was fabricated using the following materials:

(i)   Stainless steel sheet: was used for lining the drying chamber of the dryer;
(ii) Angle bar: was used for constructing the frame;
(iii) Bearings: was used for holding the agitating shaft at both ends;
(iv) Stainless steel rod: was used as the agitating shaft;
(v)   Mild steel sheet: was used as external cover for the drying chamber and the lid;

(vi) Fibre glass: was used as a lagging material;
(vii) Electrodes (both stainless and mild steel): was used for welding the various parts.

Description of the Dryer

The dryer is an in-bin type with agitator. It has a cylindrical bin as the drying chamber, with slanting and perforated floor. A shaft placed at the centre of the cylinder with spikes at alternate sides to each other serves as agitator. The agitating shaft is driven by a gear type electric motor. The upper lid of the cylinder is perforated and an opening cut-out to serve as inlet (grain hopper) for the grain to be dried. Heated air is forced into the cylinder by a centrifuged fan blowing directly on a set of heater elements. The heated air will pick moisture from the grains as it comes in contact with the grains in the chamber and releases same to the atmosphere through the perforated lid of the bin. The agitating shaft ensures even distribution of the heated air by reducing the resistance to air flow. The isometric view of the dryer is shown in **Figure 2** while **Figures 3-5** show the orthographic view and **Figure 6** shows the sectional view of the in-bin dryer.
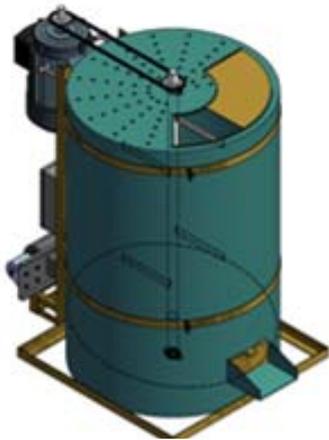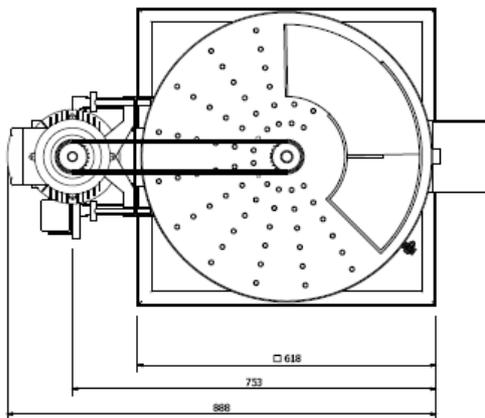

Figure 4. Front view of the dryer.

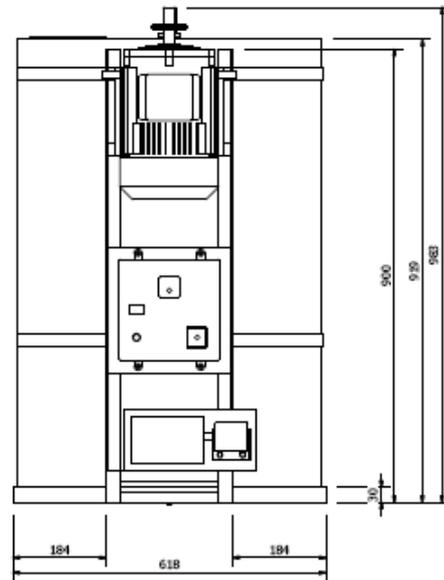**Figure 2.** The Isometric view of the dryer.

Figure 5. Side view of the dryer.

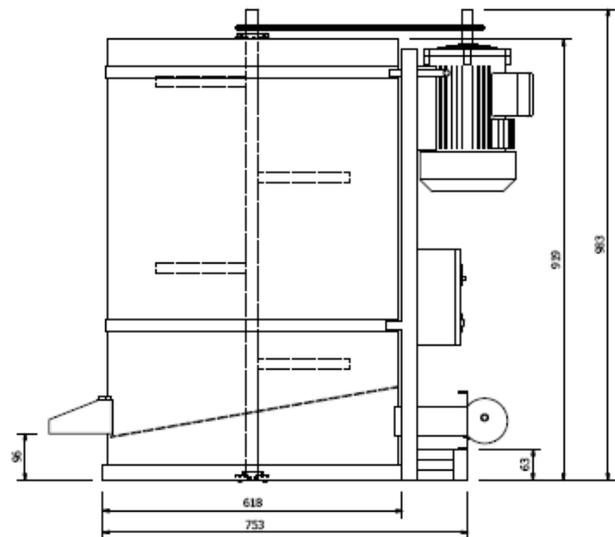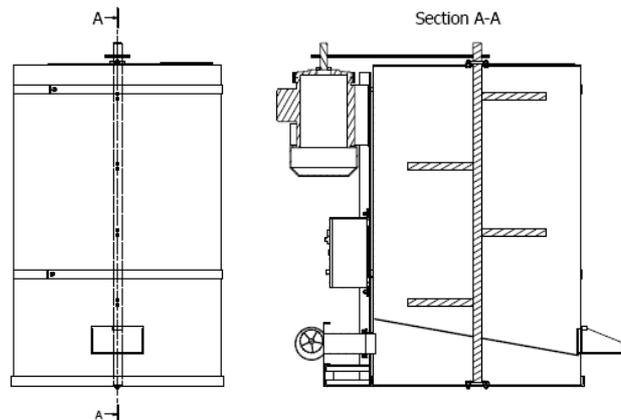**Figure 3.** Plan view of the dryer.

Figure 6. Sectional view of the dryer.

4. DATA ACQUISITION PROCEDURE

A thermostat is incorporated with the dryer to vary the temperature. It also has a blower control unit to vary the air velocity. Once the drying chamber is loaded, the blower knob is set to the required air velocity and the thermostat is also set to the required temperature, drying is then carried out for a specified time.

The dryer can be used to measure rate of drying freshly harvested maize grain at different initial moisture contents, drying air temperatures, drying air velocities and grain beds. The effects of different drying temperature, air velocity, loading and agitating speed on the quality of dried maize can be investigated with the dryer.

5. CONCLUSIONS

A batch type in-bin maize grain dryer has been developed which is capable of drying fresh maize grain at varying drying air temperature , air velocity and batch size, depending on the intended end use of the maize. The locally fabricated dryer is affordable with a total cost of sixty thousand naira (N 60,000 = 375 USD). The dryer can be used in laboratory for experimental purpose as well as on the farm for commercial scale.

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NOTATION

A_b - surface area of the blower, mm^2
A_e - surface area of the heat exchanger, mm^2
BC - Blower capacity, kg/min
Ca- specific heat capacity of air, kJ/kg℃
C_T - specific heat of maize, kJ/kg℃
D - diameter of blower, m
d - diameter of heat exchanger, m
H - static pressure, kPa
H_D - actual heat to effect drying
Hr - quantity of heat reqd for effective drying, kJ
Hr_1 - initial humidity ratio
Hr_2 - final humidity ratio
h - heat transfer rate, coefficient, NuK/d
H_L - latent heat of vapourization, kJ/kg
K - thermal conductivity of mild steel, W/m.K
mc - moisture content, %
M_R - amount of moisture remove, kg
M_x - dryer capacity per batch, kg
M_{wb} - moisture content, wet basis
N - speed of electric motor, rpm
Q_1 - initial moisture content of sample, %
Q_2 - final moisture content of sample, %
Q_a - quantity of air required for drying, kg
Q_{ht} - heat transfer rate, kJ
Q_{htr} - net heat transfer rate, kJ
q - volumetric flow rate, m^3/min
q_L - quantity of heat lost, kJ
T_B - temp. of hot air in the blower, ℃
T_{BE} - temp. difference between blower air& environ, ℃
T_c - temp. difference in dryer cabinet, ℃
T_{wm} - bulk density at a given moisture content, g/cm^3
V_a - volume of air, m^3
w_1 - initial weight of sample, kg
w_2 - final weight of sample, kg
δ_a - density of air, kg/m^3
δ_k - distance = 1 m