Development and Performance Evaluation of Thermostat Controlled Rotary Dryer for Agricultural Produce

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Abstract

Drying is ubiquitously used operation that improves on storage life of agricultural produce, either solid, liquid or slurry. Most dryers with relatively advanced technologies are expensive while the cheaper ones are manually regulated. This paper aimed at development of a direct and con-current rotary dryer that uses rolling action with hot air to effectively remove moisture from materials. The machine consists of a hopper as passage into dryer, dryer shell, heater housing, product discharge unit, shell flight, air blower for hot air distribution, thermostat for temperature regulation, temperature probe to sense the temperature from the heater as well as variable speed electric motor for power transmission. The novelty of the design is the integration of temperature regulator to the heating unit to make it thermostat-controlled. The materials for the design were selected based on strength, availability and economic value. The design calculations were done using existing machine design theories to obtain relevant design parameters. The performance evaluation showed that the machine is capable of drying various agricultural produce, say rice and yam from their initial moisture content levels of 85 and 75 % to 10 and 7 % final moisture content level respectively, at the rate of 1.2 kg/hr with the inlet air temperatures of 120° C for yam and 135 ° C for rice with humidity of 0.015. The use of machine would help to regulate drying temperature and reduce the need to manually monitor the drying process thus relieving mostly rural uses some effort in labour.

Keywords: Agriculture, Humidity, Moisture, Rotary dryer, Thermostat

1. Introduction

A primitive and ubiquitously used unit operation that reduces cost of transportation and improves on storage life of agricultural produce and materials, either solid, liquid or slurry is drying [1]. This has been in existence for preservation of food substances, building materials and crafts far before the advent of fire. Though principles behind the preservation method remain unchanged, there are lots of improvement in the techniques and machineries [1]. Different types of dryers are developed as a result of task involved and level of dryness expected. Therefore, the choice of a dryer is a function of the characteristic of the feed and expected final product [1] [2].The drying process is an operation that aims at a reduction of the moisture content in most products, industrialized or not, to guarantee their preservation in storage and transport [3] [4]. Rotary dryer uses rolling action together with hot air to effectively remove moisture from materials. Based on the design for contact between the substrate and the hot air, a dryer may be categorised as direct or indirect and con-current or counter-current. It has major parts that comprise of rotating drum that receives the feed in combination with hot air released from the heating unit. There are lifters on the inside of the drum that roll the materials through the stream of hot air to maximize the material-air contact.
The materials to be processed are retained in the drum for a specific period and temperature known as retention time in order that the materials reach the desired moisture level. Agriculture takes one of the largest shares in the economy of most African countries, and about 70-80% of the working population are engaging in it [5]. Despite the massive representation, the demand of the majority is still not met by the nation food production [4] [5]. The inadequacy and lack of good preservation and storage strategy lead to serious losses, thus reducing food supply significantly. The damages caused to food production as a result of failure of crops likewise obvious inconsistency in availability can be solved by the method of food conservation such as drying. Solar drying is the most common method of increasing the shelf life of agricultural produce in Africa [5]. There are drawbacks relating to most traditional drying methods such as spreading of crops on ground, different platforms like trays and pavement to receive sun or dry wind [5]. These lead to unhealthy and low food quality as a result of contamination by dust particles, infection by insects and rot caused by reactions of internal enzymes [6]. Also, this method is really demanding when it comes to energy and time as the crops have to be shaded at some times of the drying period [6]. Researchers have really worked on the development of rotary dryers and also redesigning of the existing ones. Performance evaluation on rotary and fluidized bed sugar dryer was carried out by [7] [8]. Some modifications were suggested especially for drum size and the velocity of the fan in order to upgrade the performance. Law and Mujumdar [9] compared rotary, flash, conveyor belt and fluidized bed dryers according to quality in terms of their design and parameter of operation. According to the power usage, they are grouped into high, low and medium, respectively. Operational design of a conventional dryer was examined by [10] [11]. These were related with capital and operational cost of rotary dryer. Rotary dryer was said to be capital intensive, but better performance due to maximum heat transfer. A more recent work was done by Agidi [12] on the development and evaluation of rotary dryer for sugar cane. The design was commendable in terms of inlet fan unit, drum assembly, fix tray and frame work. The limitation was being as special purpose built. The high temperature rotary dryers used in industrialized developed countries are only useful on the large plantations or big commercial establishment in developing countries. The chances of improving the economy of the developing nations are dependent on the production of quality and marketable products. However, on the account the low income and relatively high initial outlay of rotary dryers in developing nations, this still remains impracticable. Therefore, the introduction of low cost, smaller and locally manufactured thermostat rotary dryer suitable for drying different agricultural products with varying moisture content offers a promising alternative to reduce the tremendous post-harvest losses.

2. Materials and Method
The study involved the identification of the essential materials and design considerations. These were followed by the conceptual and detailed design of the machine using existing design theories.

2.1 Materials Selection
Material properties such as bulk density, cost, availability, corrosion resistance, tensile strength, melting temperature, weldability, machinability, and specific heat capacity were duly considered before selection for the fabrication.

2.1.1 Material for the dryer shell
The material used for the rotating drum was a 3 mm thick hot-dip zinc-coated (galvanized) steel pipe. The shell houses the material to be dried and the material during selection was customized based on the needs of the material and the process. The material was selected to meet the following requirements. Ability to withstand the relatively high operational
temperature, low cost as compared to stainless steel, low rate of corrosion in most environments, ease of machining and fabrication and high tensile strength ranging from 280-300 Mpa [13].

2.1.2 Material for the heater housing
The heater housing is made from 2.5 mm thick hot-dip zinc-coated (galvanized) steel which has high heat resistance, high strength and formability. An insulating material is used in the surrounding to reduce the heat loss during heating.

2.1.3 Material for the bearings
The copper base alloys were chose as the bearing material. These alloys are harder and stronger than the white metals (lead base and tin base alloys) and were chosen because the bearings may be subjected to heavy pressure during misalignment which causes the drum to ride harder against the roller bearing.

2.1.4 Material for the flights
A good flight design is essential to promote the gas–solid contact that is required for rapid and homogeneous drying [14]. Galvanized steel was used in flight design due to its high corrosion resistance

2.1.5 Material for the air blower
The material used for the blower and its ending is aluminium. It was chosen based on its properties; its ability to be cast into different shapes and the low cost of aluminium scrap

2.1.6 Material used for the heater housing insulation
A desirable property of a good insulator resistance to heat flow per unit thickness [14]. The space between the inner and outer heater housing was filled with fibre grass as a heat resistant binder to fill all the designed spaces.

2.2 Components of the Machine
The major components of the rotary dryer are described below:

2.2.1 Dryer Shell Unit
The material used for the rotating drum was a 3mm thick galvanized steel pipe of inside diameter 152.40mm (6’) and outer diameter 158.40mm as shown in figures 1. The internal part of the drum is designed with flight made of mild steel to pick up the materials and showers them through the air stream as the drum rotates, enhancing efficient heat transfer between the materials and drying air. The drum is made to rotate at 9.5 rpm by attaching two sprockets of 300 and 80 mm diameters to the drum and the variable speed electric motor of 2 horse power, respectively, connected by a chain. Hence, perfect velocity ratio and high transmission efficiency of 95 % are obtained.

Figure 1: Diagram of Rotary Dryer Drum
2.2.2 Heater Housing Unit
This is a fibre grass insulated rectangular housing made from 2.5mm thick zinc coated galvanized steel which has high heat resistance, high strength and formability as shown in figure 2. One heating element of 1.5kJ was fixed into the housingsuch that air channelled from air inlet unit could be heated. The amount of heat moving into the dryer unit for different drying conditions may be varied using a thermostat connected to the element linked with a temperature probe for sensing the amount of heat released per period.

2.2.3 Air Inlet Unit
The air inlet unit is incorporated at the back of the machine which is made up of a fan housing that encases the fan blade. The fan is connected with the electric motor that powers the rotation of the drum. The assembly freely fits into the heating unit.

2.2.4 Material Inlet and Delivery Unit
This is made of 2.5 mm thick galvanized plate. It is designed with reasonable dimensions for easy inflow and delivery of materials in to the dryer drum. The diagram is shown in figure 3.

2.2.5 Frame
The frame work of the machine is made of 3 mm thick angle iron s described in figure 4. The frame joints were riveted with height adjustment mechanism at the ends so as to incline the machine at angle for efficient materials-air contact and delivery of materials after drying. Figure 5 shows the exploded design of the machine.
Figure 3: Design of the Delivery Shute

Figure 4: Design of Frame of the Machine
2.3 Design Analysis and Theories

The detailed design analysis, using existing and appropriate design equations, gave the design parameters for the various components of the machine as presented in the following subsections.

A rotary dryer operating with granular, non-porous solids with unbound surface moisture is divided, in a simple scheme, in three zones [14]:

I – the first zone where the materials are raised to the temperature of the dry air, still retaining the moisture
II – the second zone where all the moisture of the materials is lost, still at the temperature of the dry air
III – the third zone where the temperature of the air raises without any further loss in moisture content

Figure 6, shows the temperature profiles in the three before mentioned zones of such simplified model for parallel flow. In the equations below, a distinction is made by labelling the variable $S_g$ which assumes the value +1 for the counter flow arrangement and -1 for the parallel (co-current) flow.

Where:

- $T_S$: Solids temperature, °C ($T_{S1}$ and $T_{S2}$ for counter flow or $T_{S2}$ and $T_{S1}$ for parallel flow)
- $T$: Moist air dry-bulb temperature, °C (where $T_3$ is ambient temperature)
- $G$: Rate of flow of air, dry-basis, kg s\(^{-1}\)
- $L$: Rate of flow of solid, dry-basis, kg s\(^{-1}\)
- $W$: Moist air absolute humidity, kg/kg
- $X$: Moisture content of the solid, dry-basis, ($X_1$ and $X_2$ for counter flow or $X_2$ and $X_1$ for parallel flow)
- $T_W$: Moist air wet-bulb temperature, °C
The capacity of the rotary dryer is determined for a case of moist non hygroscopic solid specimen (Yam) at ambient temperature of 26 °C and 75 % moisture content to be dried to 7 % final moisture at a drying rate of 1.2 kg/h. The dryer receives hot air at 135° C and humidity of 0.015. The solid specimen leaves the dryer at temperature and air speed of 80° C and 1.5 m/s, respectively. $C_{ps} = 0.85 \text{kJ/kg.K}$.

### 2.3.1 Determination of the amount of water to be evaporated

The following input parameters are required for dryer diameter calculation:

- Solid contains 75% initial moisture (Yam)
- $m_t = S_{L}(X_t - X_i) = 0.3(0.075 - 3) = 0.88kg$ (1)
- $L = M(1 - m_{c}) = 1.2(1 - 0.75) = 0.30kg/hr$ (2)
- $X_i = \frac{m_{c}}{100 - m_{c}} = \frac{0.07}{1 - 0.07} = 0.075$ (3)
- $X_2 = \frac{m_{c}}{100 - m_{c}} = \frac{0.75}{1 - 0.75} = 3$ (4)

Where:
- $M$ is the feed inlet mass flow rate, kg h$^{-1}$
- $L$ is the solids mass flow rate, dry-basis, kg h$^{-1}$
- $X_i$ is the moisture in the wet solid
- $X_2$ is the moisture in the dry solid
- $S_{L}$ is the counter flow or parallel flow identification variable

### 2.3.2 Calculation of the Diameter of the Dryer

Firstly the enthalpy of different streams is calculated and given by:

- $H_{t2} = [C_{ps} + (4.187)X_i][T_{t2} - 0]$  
  $= [0.85 + (4.187)3][26 - 0]$  
  $= 348.69 \text{KJ/kg dry air}$ (5)

- $H_{t1} = [C_{ps} + (4.187)X_i][T_{t1} - 0]$  
  $= [0.85 + (4.187)0.075][80 - 0]$  
  $= 93.122 \text{KJ/kg dry solid}$ (6)
\[ H_2 = 1.005 + (4.187)W \left[ T_2 - 2500 \right] \]
\[ H_1 = 1.005 + (1.88)W \left[ T_1 - 2500 \right] \]

Where:

- \( H_2 \) is the enthalpy of the solids at inlet to the dryer, kJ kg\(^{-1}\)
- \( H_1 \) is the enthalpy of the solids at outlet from the dryer, kJ kg\(^{-1}\)
- \( X_2 \) is the moisture content of the solids at inlet
- \( X_1 \) is the moisture content of the solids at outlet
- \( W_2 \) is the moist air absolute humidity at inlet, kg/kg
- \( W_1 \) is Moist air absolute humidity at outlet, kg/kg
- \( T_2 \) is the inlet moist air dry-bulb temperature, °C
- \( T_1 \) is the outlet moist air dry-bulb temperature, °C

Overall mass balance is given as:

\[ G(W_1 - W_2) = S_x L(X_1 - X_2) \]

Overall enthalpy balance is given as:

\[ G(H_2 - H_1) = S_x L(H_{s2} - H_{s1}) \]

Where:

The parameters for equation 14 and 15 are the same with those in equation 5 to 8

\[ G(W_1 - 0.015) = 0.88 \]

\[ W_1 = 0.0289 \]

\[ C = \frac{0.88}{0.015} = 63.30 \text{ kg} / \text{h} \]

Volume of humid inlet gas \( V_{h2} \) = 1.183 m\(^3\)/kg dry air

Volume of humid exit gas \( V_{h1} \) = 0.981 m\(^3\)/kg dry air

Shell Diameter is given as;
\[ d = \left[ \frac{4xQ_{\text{max}}}{\pi V_s} \right]^{\frac{1}{3}} \tag{18} \]

Where:
- \( V_s \) is the working velocity i.e. superficial velocity, m/s
- \( Q_{\text{max}} \) is the maximum volumetric gas flow rate, m³/h

The maximum volumetric flow rate is given as:

\[ Q_{\text{max}} = GV_{\text{max}} = 63.30 \times 1.183 = 75 \text{m}^3/\text{h} \tag{19} \]

The superficial velocity is given as:

\[ V_s = V - 0.2V = 1.5(0.2 \times 1.5) = 1.2 \text{m/s} \tag{20} \]

Where:
- \( V \) is air velocity, m/s

\[ d = \left[ \frac{4x75}{3600 \times 1.2} \right] \tag{21} \]

Hence, \( d = 0.1487 \text{m}, \text{say} 0.15\text{m} \)

### 2.3.3 Calculation of the Length of the Drum

The total length of dryer is given by

\[ L = N_{ht} \times L_{ht} \tag{22} \]

Where:
- \( L_{ht} \) is the length of heat transfer units
- \( N_{ht} = \sum N_{hi} \) is the number of heat transfer units (\( i=3 \))(23)

The temperatures of solid and gas at the boundaries of each stages were obtained using moisture and energy balances in equations 5 to 15. Thus, the number of units for heat transfer calculated for individual zone is given as:

#### Stage III

Small amount of water is converted to gas in stage III.

Enthalpy of solid at the inlet to stage III is given as:

\[ H_{s3} = [0.85 + (X_1)(4.187)](T_s - 0) = 68.74 \text{kJ/kg dry solid} \tag{24} \]

Where:
- \( T_s \) is the temperature of the air at solid positionin between stage I and II.
- Assume \( T_s = 59 \degree C \)

Heat balance over stage III

\[ S_g \times L \left[ H_{s1} - H_{s5} \right] = G(C_{ht})_{III} (T_2 - T_5) \tag{25} \]

Where:
- \( T_5 = 100.11 \degree C \) is the moist air dry-bulb temperature at location between stages III and II, \( ^\circ C \)
- \( C_{ht} \) is the humid heat of gas entering stage I, kJ/kg.k
- \( H_s \) is the solids enthalpy at solid location between III & II, kJ kg⁻¹
- Humid heat of gas entering stage I \( s \) given as

\[ C_{ht} = [1.005 + (1.88)(W_1)] = 1.059 \text{kJ/kg.K} \tag{26} \]

Where:
W1 Moist air absolute humidity at outlet, kg/kg

Adiabatic saturation temperature of air entering stage II at 100.11 °C and humidity of 0.0289 is 59.3 °C.

At the boundary 5,
\[ \Delta T_5 = T_s - T_{ss} = 41.11 °C \] (27)

At end 1,
\[ \Delta T_1 = T_i - T_{in} = 20 °C \] (28)

The logarithmic mean temperature difference at stage III is given as;
\[ LMTD_m = \frac{\Delta T_m - \Delta T_i}{\ln\left(\frac{\Delta T_m}{\Delta T_i}\right)} = 29.30 °C \] (29)

The number of transfer units at stage III is given as;
\[ (N_{ht})_{III} = \frac{T_5 - T_1}{\Delta T_m} = 0.004 \] (30)

Stage II

Using the expression for heat balance over stage II to determine \( T_4 \). The value of \( T_4 \) can be used to find the number of transfer units.

Since \( W_5 = 0.0289 \),
\[ W_5 = 178.31 \text{kJ/kg}, \quad H_4 = 124.26 \text{kJ/(kg dry solid)} \]

Enthalpy Balance at stage II is given as;
\[ H_4 = 178.05 \text{kJ/kg} \]

Where;
- \( H_s5 \) is the enthalpy of solid at the inlet to stage III, kJ kg\(^{-1}\)
- \( H_s4 \) is the enthalpy of solid at the inlet to stage I, kJ kg\(^{-1}\)
- \( H_5 \) is the moist air enthalpy at inlet to stage III, kJ kg\(^{-1}\)
- \( H_4 \) is the moist air enthalpy at inlet to stage I, kJ kg\(^{-1}\)

Once the value of \( H_4 \)is determined, \( T_4 \) can be found by applying equation 8
\[ T_4 = 134.0 °C \]

At the boundary 4, the temperature difference is given as;
\[ \Delta T_4 = T_s - T_{ss} = 77 °C \] (32)

Where;
- \( T_4 \) is the moist air dry-bulb temperature at positions between stages I and II, °C
- \( T_{ss} \) is the wet bulb temperature of the air at solid positions between I & II, °C

The logarithmic mean temperature difference at stage II is given as;
\[ LMTD_m = (\Delta T_m)_II = \frac{\Delta T_4 - \Delta T_5}{\ln\left(\frac{\Delta T_4}{\Delta T_5}\right)} \]
\[ = 57.20 °C \] (33)

The number of transfer units at stage II is given as;
\[ (N_{ht})_II = \frac{T_4 - T_5}{(\Delta T_m)_II} = 0.63 \] (34)

In order to ascertain the value of assumed exit gas temperature i.e. \( T_1 = 100 °C \), an energy balance is done over stage I using equation 15
\[ T_{GI} = 100 °C \] (35)

Stage I

At the boundary 2, the temperature difference is given as;
The logarithmic mean temperature difference at stage I is given as;
\[ \Delta T_{IMT} = \frac{T_{IT} - T_{TI}}{\ln \left( \frac{T_{IT} - T_{TI}}{\Delta T_{I}} \right)} \]

Total Number of transfer units,
\[ (N_u)_I = \frac{T_{IT} - T_{TI}}{\Delta T_{I}} = 0.011(38) \]

Length of Transfer Unit is given as;
\[ L = \frac{G \times C_H}{U_u} \]  
(40)

Where;
\[ U_u \] is the coefficient of the volumetric gas-solid heat transfer
G' is the gas mass flow rate, kg/m².s
C_H is the avg. humid heat, kJ/kg.k

The gas mass flow rate is also given as;
\[ G' = \frac{G_{avg}}{3600} \]

Where,  
G is the air mass flow rate, dry-basis, kg/h⁻¹
W2 and W1 is the moist air absolute humidity at inlet and outlet respectively, kg/kg

Volumetric heat transfer coefficient is given as;
\[ U_u = \frac{237 \times G^{0.67}}{d} = 1.408 \text{w/m}^3.\text{k}(43) \]

The average humid heat equation is given by equation 44;
\[ C_H = \frac{(C_{H1} + C_{H2})}{2} = 1.046 \text{kJ/kg.k}(44) \]

Where;
C_H1 and C_H2 is the humid heat at both ends of the dryer, kJ/kg. k
C_H1=1.033 kJ/kg. k(45)
C_H2=1.059 kJ/kg. k(46)

Length of heat transfer unit,
\[ L_u = \frac{1.027 \times 1.046}{1.408} = 0.781 \text{m}(47) \]
L=1.267×0.781=0.989m(48)

The Length to Diameter ratio for a dryer should be in the range of 3 to 10. For the above trial is 6.59. For the dryer to work efficiently it is better to reduce this ratio.
2.3.4 Determination of the Rotational Speed of the dryer

\[ N = \frac{V}{C} = 9.57\text{rpm} (49) \]

Where:

- \( N \) is the Rotational Speed, rpm
- \( V \) is the Peripheral Speed, m/min = 4.5m/min
- \( C \) is the Circumference of Dryer, \( m = \pi D \)

2.3.5. Determination of the dryer drum power requirement

\[ BHP = \frac{N(34.30 \times DW + 1.390 \times DXW + 0.73 \times W)}{100,000} \]

\[ = 0.428 \text{ BHP} \] (50)

Where:

- \( BHP \) is the break horse power required to drive drum
- \( N \) is the no of revolution per minute, rpm
- \( d \) is the diameter of drum dryer, m
- \( D \) is the riding ring diameter, m (d+2)
- \( w \) is the weight of material to be dried or live load, kg
- \( W \) is the total rotating load, kg

The load of material to be dried is given as:

\[ w = V_f \times \rho_f = 282 \times 10^6 \text{kg} (51) \]

Where:

- \( V_f \) is the volume of the shell filled with feed material, m³
- \( \rho_f \) is the density of the feed, Kg.m⁻³

Volume of shell filled with feed material is given as:

\[ V_f = \frac{\pi d_1^2 \times L \times 0.01}{4} = 1,787.6 \text{m}³ (52) \]

Where:

- \( d_1 \) is the inner diameter of the drier shell, m
- \( L \) is the length of the dryer drum, m

The rotating load is given as:

\[ W = W_d + w = 296.5 \times 10^6 \text{kg} (53) \]

Where:

- \( W_d \) is the weight of the dryer, kg
- \( W_m = V_m \rho = 14,477,486 \text{kg} (54) \)

Where:

- \( \rho \) is the density of galvanized steel = 7,900 kg/m³
- \( V_m \) is the volume of the shell material, m³

Volume of the shell material is given as:

\[ V_m = \frac{(\pi d_2^2 - \pi d_1^2) \times L}{4} = 1832.6 \text{m}³ (55) \]

Where:

- \( d_2 \) is the outer diameter of the drier shell, m
- \( d_1 \) is the inner diameter of the drier shell, m
- \( L \) is the length of the dryer drum, m

Assume Hold up = 0.1
\[ D = (0.15 + 2) = 2.15 \text{m} \] (56)

### 2.3.6. Determination of air blower power requirement

The power of air blower depends on volume of air entering the blower and the temperature of the air inlet.

The blower power \( P_b \) is expressed as:

\[ P_b = 2.72 \times 10^{-5} \times Q \times p = 0.135 \text{ KW} \] (57)

Where:

- \( Q \) is the fan volume, m\(^3\)/hr
- \( p \) is the blower operating pressure, 100 cm water column

Fan volume is given as:

\[ Q = \frac{G_{\text{max}} \times 22.4 \times T_{\text{atm}}}{9.9 \times T_{\text{air}}} = 49.55 \text{ m}^3/\text{hr} \] (58)

Where:

- \( T_{\text{ai}} \) is the inlet air temperature, K
- \( G_{\text{max}} \) is the maximum mass flow of air required for drying, kg/hr = 63.30 Kg/hr
- \( T_{\text{atm}} \) is the atmospheric temperature air, K
- Temperature of the inlet air = 30 °C

### 2.4. Components and Assembling Process

Having fabricated all components of the rotary dryer as described in figures 1-5 above, the assembly of the dryer components carried out is shown in figure 7.

Figure 7: Assembled Rotary Dryer

### 3. Performance Evaluation

A known mass (100g) of the solid were prepared in accordance with ASAE standard S358.2 [17] in line with the work of [18] [19] with initial moisture content determined, was fed into the dryer at steady state. There was drop in outlet air temperature after a short time to a point due to heat absorption by the feed from the inlet hot air. Table 1 shows the experimental condition of the dryer set up. The intermittent drying process through the dryer takes 10 minutes when the sample was reweighed to record moisture loss data and refed into the dryer. The test took total of 110 minutes and 100 minutes respectively for rice and yam at constant inlet air velocity and temperature until no change in mass were recorded for the feeds, taken as equilibrium moisture with the surroundings.

| Experiments | Variable | Constant Parameters |
|-------------|----------|---------------------|
| Experiment 1 | Rice     | temperature of the Inlet air = 120°C |
|             |          | velocity of the Inlet air = 1.397 m/s |
|             |          | speed of the Drum = 8 rpm |
|             |          | Humidity = 50% |
Experiment 2  Yam  

Inlet air temperature = 135°C  
velocity of the Inlet air = 1.397 m/s  
speed of the Drum = 8 rpm  
Humidity = 50%  
Mass of feed = 100 g on wet basis

Convention dictates that moisture content, moisture ratio, drying rate of feed and drying constant on wet basis are written as:

$$X = \frac{M_w}{M_w + M_c} \times 100 \quad (59)$$

Where:

- $M_w$ is the mass of water, %
- $M_c$ is the mass of dry solid, %

$$MR = \frac{M_i - M_f}{M_i - M_f} = e^{-kt} \quad (60)$$

$$K = -\ln \frac{MR}{t} \quad (61)$$

Drying rate for the feeds are calculated for period of 10 minute using the equation 62;

$$\text{drying rate} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Time interval}} \quad (62)$$

Where $MR$ is moisture ratio, $M_i$ is the initial moisture content, $M_f$ is the final moisture content, $M_t$ is the moisture content at time $t$ and $K$ is the drying constant.

4.0 Results and Discussion

The results of the drying for rice and yam were presented in Tables 2 and 3, Figures 8 and 9 respectively, for the various drying parameters.

4.1 Results for Drying of Rice and Yam

Moisture loss data for rice and yam are presented in Tables 2 and 3 below. Also, the effects of drying parameters on the drying rates and constants are presented in Figures 8 and 9.

| Drying Time (Min) | Mass of Feed on Wb (g) | Mass of Feed on Db (g) | Mass of Water (g) | % Moisture Retained | Drying Rate (g/min) | Moisture Ratio | Drying Constant (/Min) |
|-------------------|------------------------|------------------------|-------------------|---------------------|---------------------|----------------|------------------------|
| 0                 | 100                    | 15                     | 85                | 85                  | 0                   | 1              | 0                      |
| 10                | 92.5                   | 15                     | 77.5              | 83.7                | 0.75                | 0.98           | 0.00202               |
| Drying Time (Min) | Mass of Feed on Wb (g) | Mass of Feed on Db (g) | Mass of Water (g) | % Moisture Retained | Drying Rate (g/min) | Moisture Ratio | Drying Constant (Min) |
|-------------------|------------------------|-----------------------|------------------|--------------------|---------------------|----------------|----------------------|
| 0                 | 100                    | 25                    | 75               | 75                 | 0                   | 1              | 0                    |
| 10                | 90                     | 25                    | 65               | 72.2               | 1                   | 0.96           | 0.00408              |
| 20                | 80                     | 25                    | 55               | 68.8               | 0.5                 | 0.9            | 0.00527              |
| 30                | 71                     | 25                    | 46               | 64.8               | 0.3                 | 0.85           | 0.00542              |
| 40                | 62                     | 25                    | 37               | 60                 | 0.23                | 0.78           | 0.00621              |
| 50                | 53                     | 25                    | 28               | 53                 | 0.18                | 0.68           | 0.00771              |
| 60                | 46                     | 25                    | 21               | 46                 | 0.12                | 0.57           | 0.00934              |
| 70                | 39                     | 25                    | 14               | 36                 | 0.1                 | 0.43           | 0.012                |
| 80                | 34                     | 25                    | 9                | 26                 | 0.06                | 0.28           | 0.016                |
| 90                | 29                     | 25                    | 4                | 14                 | 0.055               | 0.1            | 0.025                |
| 100               | 27                     | 25                    | 2                | 7                  | 0.02                | 0              | 0                    |

Table 3 Moisture Loss Data for yam at 135°C Inlet Air Temperature and 1.397 m/s Inlet Air Velocity
4.2 Discussion of Results

Tables 2 and 3 show moisture loss data for drying process of rice and yam, over a period of 110 and 100 minutes respectively. Also, Figures 8 and 9 show the effect of drying parameters (inlet air velocity and temperature) on the drying rate and constant for rice and yam. Figure 8 shows relationship between drying rate and time. The trend in the drying process of rice and yam are similar as they both decrease as the time progresses and attained the permissible percentage moisture of 10 and 7 % at 110 and 100 minutes respectively. It was observed that both rice and yam lost majority of their moisture contents at around 50 minutes of the drying process, compared to the later period. This shows that drying rate is seriously
dependent on air velocity and temperature [18] and low internal resistance of the water molecules at the initial stage, thus energy impact easily broke the bonds [18] [20]. As the drying progresses, the rate decreases due to compactness of the molecules of the products and more energy is required for bond breaking and since constant energy is been used, longer time is required for the same [18]. Comparing drying rate of rice and yam in figure 8, at 30 minutes, 70 % of the moisture has been lost in yam compared to rice of about 60% lost in moisture content. This is also supported by [18] [20] [21] that temperature has much effect on the drying rate.

Figure 9 shows the relationship between drying constant and time for both rice and yam. The values for drying constant was gotten from the slope of moisture ratio and time, expressed by equations 60 and 61. It was observed that a positive linear relationship exist between drying constant and drying time. There is an indication that temperature is a major determinant when comparing the two curve.

5.0 Conclusion

A development of an effective thermostat controlled rotary dryer for agricultural produces has been achieved. The design and construction were based on existing engineering design models.

The performance evaluation of the machine shows that inlet air temperature and velocity are the major determinant for the drying process. There is linear positive relationship between drying constant and time, linear negative relationship exist between drying rate and time.

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