International Journal of Engineering Research and Development
e-ISSN: 2278-067X, **p**-ISSN: 2278-800X, www.ijerd.com
Volume 7, Issue 9 (July 2013), PP. 10-15

Design Modelling of a Fluidized Bed for Grain Drying

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Abstract:- The performance of fluidized bed dryer for grain drying is highly dependent on the process modeling. This work exposes the salient features that characterize fluidized bed performance using the crop and operating parameters to form empirical sub-models. This research is geared towards equipping the engineers with design and modeling tools for quantifying the activities and relationship of various processes in a fluidized bed dryer for better productivity.

Keywords:- performance, modelling, grain drying, fluidized bed dryer, fluidization bed velocity,

I. INTRODUCTION

Grains are highly consumed in most countries of the world; however they are cultivated annually and most times harvested once a year without guarantee of produce. This implies that in order to meet the ever growing demand of grain consumption, most of the global production of maize, wheat, rice, sorghum and millet must be held in storage for periods varying from one month up to more than a year [1]. One of the major challenges facing grain storage is the moisture content of grain. High moisture content leads to storage problems because it exposes grains to fungal and insect problems, respiration and germination [2] and to avert these problems farmers are faced with the issue of grain drying. The best theoretically and practically known problems in the drying of agricultural products are processes of the convection drying of particles of solids forming fixed beds, particularly the drying of grain [3] & [4]. On harvesting grain, the moisture content ranges from 16% to 28% (wb) [3]. The longer the grain needs to be stored the lower the required moisture content will need to be, although a rule of thumb for seed states that the life of the seed will be halved for every 1% increase in moisture content or a 5^oC increase in storage temperature. Table I below shows the safe moisture content applicable to different storage periods.

Table I: Safe Moisture Content for Different Storage periods [?]

Storage Period	Require Moisture Content for Safe Storage
2 to 3 weeks	14 to 18%
8 to 12 months	12 to 13%
More than 1 year	9% or less

Traditional methods used by most farmers for drying rely on natural air movement to reduce moisture content to a safe level for storage. In addition they may utilize the extra drying capacity gained by exposing the produce to the sun

In the Philippines, De Padua et al. (1986) [5], Adamczak et al. (1987) [6], Driscoll et al. (1987) [7], Tumambing et al. (1988) [9] and Tumambing et al. (1989) [10] recommended that wet grain handling problems can be properly and practically solved by drying the high moisture grain in two stages, thus to rapidly dry the high moisture content grain (>24%) down to a more manageable level (about 18%) using a high speed dryer and then to about 14% using a batch dryer or sun drying. The major setback with the “two stage” drying is brought about by the dryers used for pre-drying. Also the control of the grain temperature is difficult, since there are temperature and moisture gradients that exist within the different zones of the dryer. This leads to lack of uniformity in grain drying and to the thermal damage of the grain which can affect the seed viability, head grain yield and colour. Fluidized bed drying as a rapid pre-drying method is an interesting alternative since the thorough mixing that the grains undergo during fluidization ensures a good homogeneity of the thermal treatment of the product and a more stringent control of the grain dryers [11]. Also shorter drying time is achieved as a result of high rate of heat and moisture transfer between the grain and the surrounding air.

Researchers in the past simulated fluidized bed drying using single and multi phase models. In a single phase model, the fluidized bed is regarded essentially as a continuum; heat and mass balance are applied over the fluidized bed [12]. It is assumed that particles in the bed are perfectly mixed [13]. In a multi phase model, the fluidized bed is considered to be made up of the bubble phase (dilute phase) and a suspension (dense phase) phase. Although Burgschweiger et al. (1999) [14] and Zahed et al. (1995) [15] assumed the suspension phase itself to be composed of the particles and intermediate gas phase. Numerous researchers have come up with empirical or semi-empirical models to simulate grain drying using this fluidized bed application. A series of empirical models based on exponential time decay have been developed to represent the drying kinetics of agricultural materials in fluidized bed dryer [16], [17] & [18]. The page model was found to match the experimental data very closely for mustard drying [18].

The aim of this study is to develop mathematical sub-models to describe various activities and relationships that occurs in a fluidized bed drying system and hence form a broader design model for fluidized bed drying systems. Also validation options are given to evaluate worthiness of developed models

II. ANALYSIS AND MODELLING OF THE FLUIDIZATION PROCESS

To successfully carryout this derivation, some physical properties of the grain has to be evaluated. Below are the physical properties to be evaluated.

- Shape of grain
- Size, dp * 10^{-3} (m)
- Bulk density (kg/m^3)
- Porosity (%, m^3/m^3)
- Equilibrium moisture contents corresponding to fluidized air temperaturs (% d.b)
- Initial moisture content of grain (% d.b)
- Temperature of fluidizing air (^oC)
- Fluidizing air velocity (m/s)
- Solids holdup (kg)
- Initial stagnant bed height

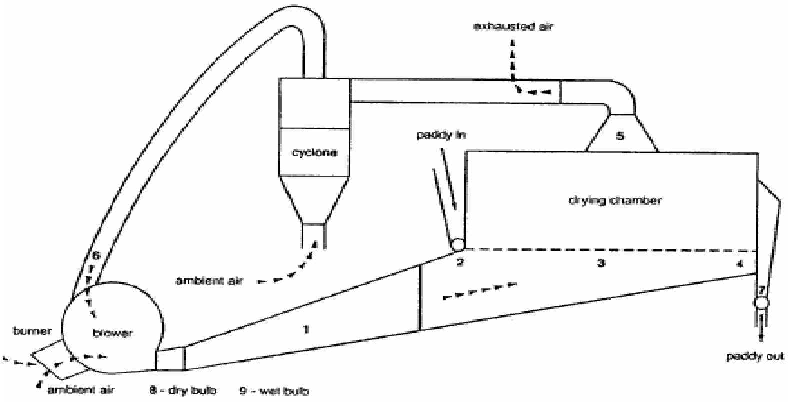

Fig. 1: Diagram of a fluidized bed dryer [28]

The equilibrium moisture content was postulated by [19] as a function of temperature and relative humidity of the fluidizing air. i.e

$$M_e = \left(\frac{ln(1 - RH)}{-4.723 * 10^{-6}(1.8T + 491.7)} \right)^{1/2.386} \qquad (1)$$

Where T is the fluidizing air temperature in ^oC and RH is the relative humidity of fluidizing air

In the development of the sub-models, the various assumptions were made:

- The fluidizing air flows uniformly perpendicular to the grain flow
- The grain particles move in a perfect plug flow in the longitudinal direction. This situation is achieved in a channel with length to width ratio of at least 10:1
- Uniform temperature is maintained within the grain kernel
- The process is adiabatic with negligible heat and air losses in the system
- The moisture level within the grain kernel is uniform
- The heat capacities of moist air and water vapour remains the same over the valid temperature range
- The grain moisture evaporates as a result of the fluidizing temperature
- The fluidized bed drying system is assumed to operate on diffusion principle
- The residence time of grain is assumed constant

Analysis of discrete stages and activities of the fluidized bed drying system gives birth to the empirical sub-models as shown below

A. Moisture Balance Sub-Model

For moisture balance, $\dot{m}_a dH = \dot{m}_g dM$ (2)

Simplifying further, $\dot{m}_a(H_f - H_i) = -\dot{m}_g(M_i - M_f)$ (3)

$(H_f - H_i) = \mu(M_i - M_f)$ (4)

Where μ = dimensionless ratio $(\dot{m}_g / \dot{m}_a)$

$\dot{m}_g$ = mass flow rate of dry grain, (kg dry grain/s)

= $\dot{m}_{gw}(1 - M_o)$ (5)

$\dot{m}_{gw}$ = mass flow rate of wet grain, (kgwetgrain/s)

$\dot{m}_a$ = mass flow rate of air at increment Δx.

= $\rho_a W v_a \Delta x$ (6)

ρ_a = density of the inlet air, kg/m^3

W = width of the grain bed (m)

v_a = superficial air velocity, m/s

H_f = absolute humidity of exhaust air, kg H_2O/kg dry air

H_i = absolute humidity of inlet air, kg H_2O/kg dry air

M_i = initial grain moisture content at increment Δx, kg H_2O/kg dry grain

M_f = final grain moisture content at increment Δx, kg H_2O/kg dry grain

Solving equation 4 for H_f yields

$H_f = H_i + \mu(M_i - M_f)$ (7)

B. Energy Balance Sub-Model

For energy balance, $\mu dh_g = -dh_a$ (8)

i.e $\mu(h_{gf} - h_{gi}) = (h_{ai} - h_{af})$ (9)

where h_{gf} = final grain enthalpy at increment Δx, (kJ/kg dry grain)

h_{af} = outlet air enthalpy at increment Δx, (kJ/kg dry air)

h_{ai} = inlet air enthalpy at increment Δx, (kJ/kg dry air)

Enthalpy is known to a product of specific heat capacity and temperature, i.e

$h = CT$ (10)

The enthalpies of the initial and final states of the grain and air are:

$h_{gi} = C_{gi}T_{gi}$ (11)

$h_{gf} = C_{gf}T_{gf}$ (12)

$h_{ai} = C_aT_{ai} + H_i(C_vT_{ai} + \lambda_o)$ (13)

$h_{af} = C_aT_{af} + H_f(C_vT_{af} + \lambda_o)$ (14)

Where C_{gi} = initial specific heat capacity of wet grain at increment Δx, (kJ/kg °C)

C_{gf} = final specific heat capacity of wet grain at increment Δx, (kJ/kg °C)

C_a = specific heat capacity of the air, (kJ/kg °C)

C_v = specific heat capacity of water vapour, (kJ/kg °C)

T_{gi} = initial temperature of the grain at increment Δx, °C

T_{gf} = final temperature of the grain at increment Δx, °C

T_{ai} = inlet air temperature, °C

T_{af} = exhaust air temperature, °C

λ_o = enthalpy saturated vapour at 10°C, kJ/kg

C. Heat Transfer Rate Sub-Model

The heat transfer rate equation is adopted as:

$$m_g\,dhg = h_{tc}(T_{ai} - T_{gi})a_v\,dV - m_g\,dM[h_{fg} + C_v(T_{ai} - T_{gi})]$$ [20] (15)

Where h_{tc} = heat transfer coefficient, (kJ/s $m^2\,{}^oC$)

a_v = specific grain surface area, (m^2/m^3)

dV = differential bed volume, m^3

$= WH_u\Delta x$ (16)

H_u = static (unfluidized) bed depth, m

h_{fg} = latent heat of vapourization of water in the grain at temperature T_{gi}, kJ/kg

From equation 5 to 15, the final grain temperature T_{gf} and the outlet air temperature T_{af} at each different element can be formed as

$$T_{gf} = \frac{C_{gi}T_{gi} + q - C}{C_{gf}}$$ (17)

$$T_{af} = \frac{h_{af} - \lambda_o H_f}{C_a + C_v H_f}$$ (18)

Where $q = h_{tc}(T_{ai} - T_{gi})_{av}dV$ (19)

$$C = m_g\,dM[h_{fg} + C_v(T_{ai} - T_{gi})]$$ (20)

D. Dry Rate Sub-Model

From the two term exponential model:

$$M_f = (M_o - M_e)(Ae^{-K_1t} + Be^{-K_2t} + M_e)$$ [12] (21)

Where M_f = grain moisture content at time t, (kg H_2O/kg wet grain)

M_o = initial grain moisture content, (kg H_2O/kg wet grain)

M_e = equilibrium moisture content, (kg H_2O/kg wet grain)

A, B = dimensionless coefficients

K_1, K_2 = first and second term drying constants (min^{-1})

From the 8th assumption as mentioned above, if the fluidized bed is considered to operate on a diffusion principle, there is therefore the need to derive diffusion related expressions. During the drying process, water that is displaced from the grain to the air encounters resistance in the grain characterized by a diffusion coefficient "D" and resistance n the air characterized also by a mass transfer coefficient k.

The Biot number gives a ration of this resistance i.e.

$$B_i = \frac{KmR}{D}$$ (22)

Where R is the radius of the grain

m describes the equilibrium between the water concentration in the air, C_{air} and in the grain C, given by

$$m = \frac{C_{air}}{C}$$ (23)

The expression for obtaining the mass transfer coefficient k [22] is adopted

$$K = \frac{(0.765R_e{}^{-0.82} + 0.365R_e{}^{-0.386})v_a}{\in Sc^{2/3}}$$ (24)

Where $\in$ is the porosity of the fluidized bed

R_e is the Reynolds number related to the superficial velocity v_a and the grain diameter d as

$$R_e = \frac{\rho_{air}\cdot v_a\cdot d}{\mu_{air}}$$ (25)

And Sc the Schmidt-number also given by

$$Sc = \frac{\mu_{air}}{\rho_{air}D_{air}}$$ (26)

Where μ_{air} is the viscosity of air,

ρ_{air} is the density of air and

D_{air} the diffusion coefficient of water in air.

Most grains are assumed to be spherical in shape, but for those with a different shape, the diameter is calculated thus

$$d_s = \sqrt[3]{\frac{6M_m}{\pi \rho m}} \qquad (27)$$

Where M_m is the mass in kg of m number of grain in the sample,
ρ is the density of grain in kg/m^3 and
m is the number of solid particles.

The moisture ratio of the grain during drying can be expressed as

$$MR = \frac{M_f - M_e}{M_i - M_e} \qquad (28)$$

Where M_f = final moisture content of grain (db)
M_e = equilibrium moisture content of grain (db)
M_i = initial moisture content of grain.

III. VERIFICATION

To validate a fluidized bed model, the predictions from the model is compared with the experimental results of the researcher or with the experimental results of the researchers. In the past, researchers have come up with mind blowing results which have stood the test of time and hence their works can be used as a yard stick for validation. The validation process can be done at different levels

- Fitting the drying curves of the researcher with that of the model to be used for validation to ascertain the goodness of fit
- Performing non-linear regression analysis using statistical soft wares, example SPSS
- Obtaining the coefficient of determination (R^2)

The goodness of fit of the models can also be obtained by other statistical parameters such as “X^2” (reduced mean square of deviation) and “RMSE” (Root mean square error). These values are calculated as follows

$$X^2 = \sum_{i=1}^{N} \frac{\left(MR_{pre} - MR_{exp}\right)^2}{N - P}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre} - MR_{exp}\right)^2\right]^{1/2}$$

Where MR_{pre} is the moisture ratio of the predicted model and MR_{exp} is the experimental moisture ratio. N the number of observations and P is the number of parameters in the regression model.
The acceptability of a drying model is based on a value for R^2 which should be close to 1 and low values of X^2 and RMSE.

IV. CONCLUSIONS

The drying performance of a fluidized bed dryer can be assessed in terms of drying time, drying capacity, moisture ratio, maximum dry air and product temperatures as well as product quality. This research is geared towards equipping the agricultural engineers with design and modeling tools for quantifying the activities and relationship of various processes in a fluidized bed dryer for better productivity. An insight into the simulation and validation of models is also done. This work has therefore generated empirical sub-models using statistical tools.

ACKNOWLEDGMENT

My heartfelt appreciation goes to Prof. Adeniyi Jones and Prof E.I.E Ofodile for their support and guidance in the course of this study. Also my deepest gratitude goes to Engr. Nwabueze Iwuchukwu owing to his contributions to the success of this work.

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