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Simulation Model to Predict Drying in the Automated Grain Dryer

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Abstract

The research study was carried out with the aim of developing a simulation model to control moisture content and temperature ina grain drying chamber. Through the use of mathematical models of deep bed grain drying, consisting of three sets of equations- mass balance equation, drying rate equation and energy balance equation an algorithm was coded througha visual basic computer program to simulate the grain drying. Data simulated by the program was compared with actual results. From the simulated results it was observed that there was a strong correlation between moisture content and drying time for both simulated and experimental data (R^2=0.929 and 0.894 respectively for simulated and actual data). In addition there was a strong linear correlation between simulated and experimental moisture content (R^2=0.989). The decrease in moisture content with time was exponential. Besides, temperature and moisture content were reducing with time while air humidity was increasing for both simulated and experimental data. The developed simulation model can be used to predict drying in the automated grain dryer. With the automation of the drying system, controlling of the drying environment is possible, and this minimizes losses and improves storage of the grains.

Keywords: Grain drying chamber, deep bed grain drying, moisture content, drying time, air humidity.

Introduction

Drying is a phase in post harvesting in which moisture content is reduced to suitable level for safe storage. The aim of this process is to lower the moisture in order to guarantee conditions favorable for storage or other processing of the product. Drying reduces loss causes such as premature and unseasonal germination of grain and infestation by insects and fungi[1].When Grain is in the field it dries naturally until it reaches equilibrium moisture content. Conditions become less favorable for further drying of grain to safe moisture content for storage. This has led to the use of mechanical driers which are not efficient due to properly unmonitored conditions which may lead to hot spots, loss of grain nutrition and viability. In mechanical drying the usual recommendation is to run the natural air continuously to avoid the problem of the operator leaving the fan off for too long and possibly creating spoilage conditions in the bin. However this means the fan runs many times when no drying is done or worse yet under conditions when moisture can be added to the grain in case of wet inlet air. These call for development of a grain drying simulation model to monitor these conditions.

The highlighted conditions can be addressed using a simulation program with the capability to address several attendant facts suitable to run the fan and heater under some set of rules. These facts are: first, sincethe difference of the dew point temperature of the input and the exhaust air is a direct indicator of the absolute humidity of the air, an input dew point indication higher than exhaust dew point reading means that allowing the fan to run would add moisture to the grain; second, the since the grain moisture content affects the quantity and quality of grain, as well as grain storability, it may also affect the economic return; third, since the rate of moisture loss from the grain increases with temperature and that less air is required to maintain the same drying rate, increasing air temperature can reduce the quantity of fuel consumed; Storage lifeof grain is determined by temperature and the moisture content at which it is stored; Inorder to obtain the moisture content, temperature and remaining storage life of the wettest grain in the bin then the simulation program has to refer to the input data on ambient air conditions for the input air dew point and temperature. The Exhaust air dew point and temperature could on the other hand be obtained from the simulation. In proposing our model, we relied on the work of several authors who have developed simulation models for analysis of deep bed grain drying. In addition, we also considered related studies on Simulation of natural air drying of maize in cribs carried out by B.K Bala, et al[2]. We however established that no studies have been carried out aimed at simulation of mechanical grain drying where fan and heater are used.

Based on these facts, the study proposed a simulation model designed touse humidity and temperature to simulate fan and heater according to preset conditions. The simulation was used for automatic controls to relieve the operator of some management tasks and reduce human errors.

Material and Methods

Description of the Experimental Site: The grain drying chamber was designed and fabricated in the Biomechanical and Environmental Engineering Department workshop of the Jomo Kenyatta University of Agriculture and Technology, in Juja Township 10 km West of Thika town and 45km East of Nairobi, Kenya.

Description of the Drying Chamber: This consisted of a plenum chamber with a fan and a heater, agitator, and the grain drying chamber. Air entered in the plenum chamber where it was heated evenly mixed and then fanned in the grain drying chamber. The drying air passed through the exhaust to the outside. Agitation was one to provide even drying by avoiding accumulation of moisture on the top grain and occurrence of any hot points in the drying chamber. All the above applications lead to proper utilization of resources and saving of energy. The drying chamber was 0.78m wide and 2m high. The drying chamber was made of galvanized iron sheets, painted with iron oxide to suit for outdoor operation. It is circular in design with wide hot air inlet and exhaust to allow air to mix and spread in the drying chamber to promote even drying. Fan is further away from the grain to reduce the chances of grain lift off especially the light grains. Discharge is done through the hopper

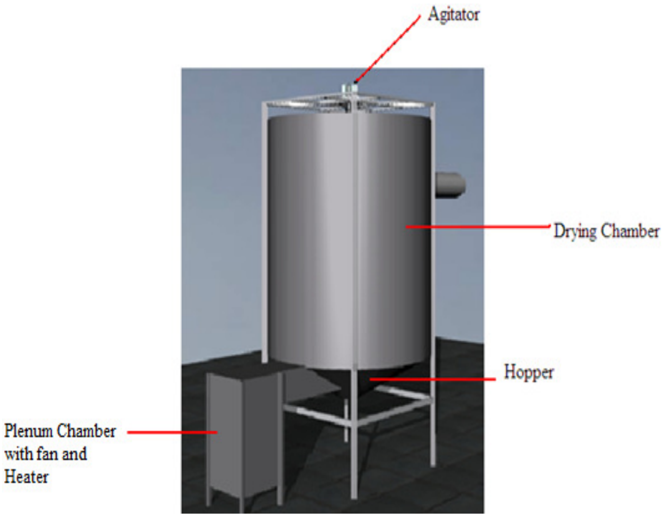

Figure-1
Grain drying chamber

Grain Drying Model: Drying is amass transfer process involving removal of water by evaporation where applied heat by convection carries away vapour as humidity. Drying of hygroscopic-porous products such as grain is quite complex. Moisture within grain moves in the form of a liquid and/or vapor. Various physical mechanisms for moisture removal have been proposed. Deep bed dryer model development follows as below. A bed of grain of cross sectional area A and height L is represented in the elemental layer as shown in Figure 2. The drying model is developed over elemental control volume of a unit cross section and of height z. The liquid movement can be due to capillary flow because of surface forces, liquid diffusion due to moisture concentration difference, surface diffusion, vapor diffusion, thermal diffusion due to temperature difference and hydrodynamic flow[3].

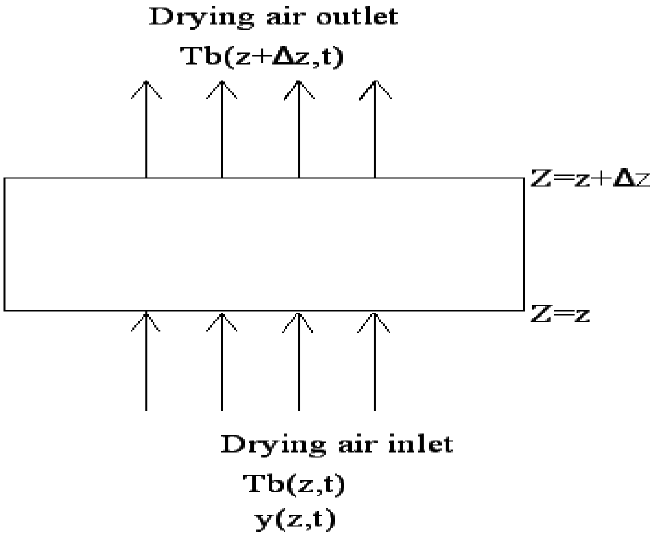

Figure-2
Elemental bed of corn grains

Assumptions applicable in analysis of bin sectioninclude no shrinkage during drying; air flow is restricted to a uni-directional in the x and y directions respectively ;in the bin chamberthermal conduction between two grain particles is negligible and there is no conductive heat losses within the drying bin; within an individual particle temperature gradient is negligible; the drying chamber walls are adiabatic and has negligible heat capacities; within short time intervals heat capacities of the grain and air are constant; there is no heat gain or loss from the hopper other than heat loss calculable through overall heat loss coefficient; grain kernels are uniform in size and internally homogeneous/isotropic spheres; moisture migration path within each particle is in the radial direction only due to liquid diffusion; and the amount of moisture on grain surface takes a volume of dynamic fixed (equilibrium) moisture content[3-5]. The analysis of drying in a deep bed would in mass balance, energy balance, energy exchange rate between the drying material and the drying media, and the drying rate. In the plenum chamber section the heater is supplying energy Q watts at a rate given by its rating

This energy is used to heat air and raise its temperature by:

$$Q = \dot{m}_a\left(C_{pa} + HC_{pv}\right)(T - T_\infty) \qquad (1)$$

In the bin there is:

The rate of incoming hot air loosingits heat at a rate given by: $\dot{M}_a(C_{pa}+C_{PV}H)\,\Delta T_a$ (2)

The grain gains heat at a rate given by:

$mg(c_{pg}+c_{pw}m)\,\frac{\partial T_g}{\partial t}$ (3)

Evaporating moisture gains latent heat of vaporization given by: $M_g h_{fg}\frac{\partial m}{\partial t}$ (4)

The vaporized steam is heated to temperatures of the heating air released to the temperatures of the air given by: $m_g c_{pv}(Ta-Tg)\,\frac{\partial m}{\partial t}$ (5)

Mass Balance: The change of humidity in the drying chamber as expressed by Bala[4], Dimitriadis and Akritidis[5], and Garg and Prakash[3], is given by;

$$\frac{\Delta H}{\Delta Z} = -\frac{\rho\partial M}{G_a\partial t} \tag{6}$$

The flow rate is evaluated from

$$G_a = \frac{\dot{M}_a}{A} = \rho_a V_a \tag{7}$$

The humidity generation in the drying chamber can be analyzed by equation 6, in which as the humidity in the chamber increases towards saturation vapor pressure, the drying rate reduces. As a result it may necessitate alteration of the air flow pattern, based on the rate of humidity generation. The vapor pressure due to the moisture evaporated from the drying grain must never exceed the saturated vapor pressure. It was necessary to evaluate the vapor pressure against saturation vapor pressure so as to monitor the contribution of humidity to the drying process. Tiwari et al. gave the properties of drying air as in table 1, in which ρ_v is the density of drying air (kg/m^3), P(T) the partial vapor pressure (Pa) at temperature T (K).

Table-1
Properties of Drying Air

Property	Value	Property	Value
K_V	0.0244	μ	$1.718*10^{-5}$
C_{pa}	$999.2+0.143\ (T_a-273.15)$	ρ_a	$353.44/T_a$
P(T)	$\text{Exp } 25.317-5144/T_a$		

The saturated vapour pressure P_s (Pa) at temperature T (K) is derived from the equation given by Hahn as

$$PS = RS[EXP\left[\frac{AS+BT_a+CT_a^2+DT_a^3+ET_a^4}{FT_a-GT_a^2}\right]] \tag{8}$$

The parameters in equation 8 were as presented in table 1

Table-1
Parameters in Equation 8

Parameter	Value	Parameter	Value
R_s	22,105,649.25	D	$0.12558\text{x}10^{-3}$
A_s	-27,405.526	E	$-0.48502\text{x}10^{-7}$
B	97.5413	F	4.34903
C	-0.146244	G	$0.39381\text{x}10^{-2}$

Source: Hahn (1990)

Partial vapour pressure P (T) equation in Table 1 and Equation 8 are useful in evaluating the vapor pressure against saturation vapor pressure.

The temperature at any point in the bin is given by:

$$T_z = \frac{T_{z+1}+\rho_g\Delta Z}{G_a*(C_{pa}+H*C_{pv})} * \frac{\Delta M_t}{\Delta t} * h_{fg} \tag{9}$$

The Drying Rate Analysis

The drying rate equation for thin layer drying given is expressed as[3-4]

$$\frac{\partial m}{\partial t} = k(M-M_e) \tag{10}$$

Equation (8) can be evaluated with its boundary condition as expressed as[6]

$$\left\{\begin{Bmatrix} M(t_0,u) = M_0 \\ M(t_e,u) = M_e \end{Bmatrix}\right. \tag{11}$$

The Newton's solution model to equation 8 is expressed as [7]

$$M_R = \frac{M-M_e}{M_0-M_e} = Exp(-kt) \tag{12}$$

Data Acquisition and Model Performance

Simulation algorithm: An algorithm coded using Visual Basic 6 was developed to model the drying process build around the flowchart below and equations 1 to 11. The input parameters included grain temperature, grain moisture content, input air temperature and grain storage life. The simulation process is as shown in figure 3.

Experimental set-up: The schematic diagram in figure-3 represents the experimental set up. The bin was divided into a number of layers of 0.03 m so that the properties of the material are constant or nearly so within each layer. For economy of computing time a compromise between the acceptability of the results and intervals was used so the conditions were checked after every hour for ten hours. The drying air inlet air temperature, initial grain moisture content and temperature were measured and recorded. It was assumed that the initial air temperature was equal to the initial grain temperature. These conditions were used for the simulation and the results compared at height 0.03m.

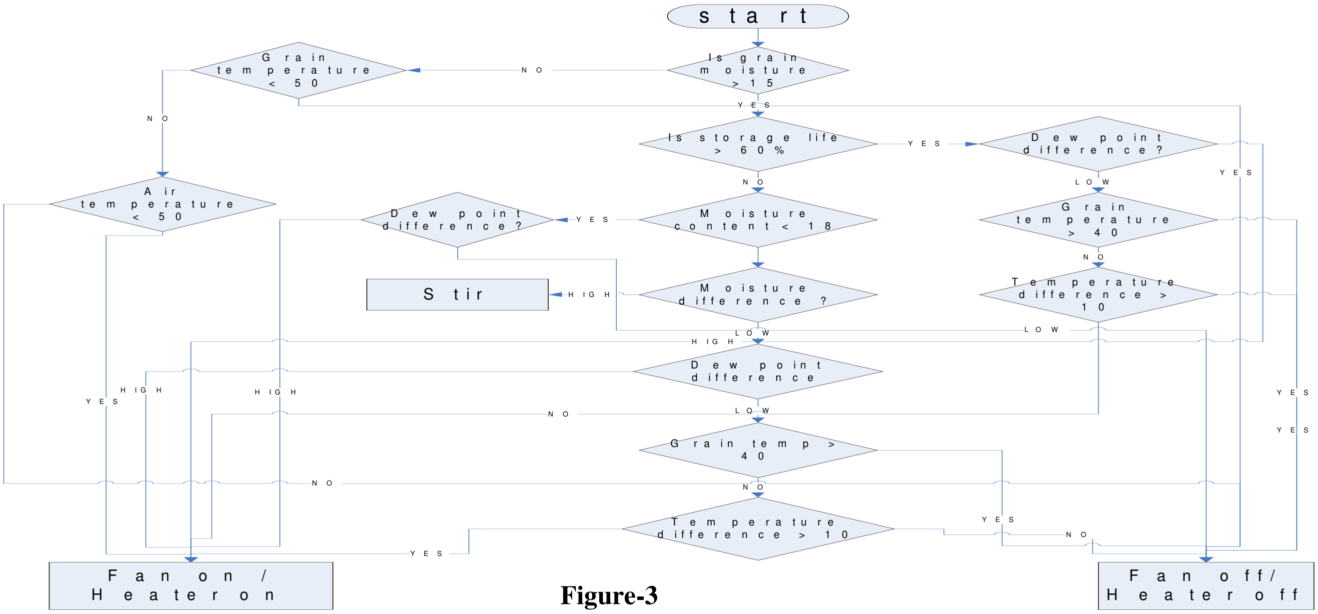

Figure-3
The simulation algorithm flow chart

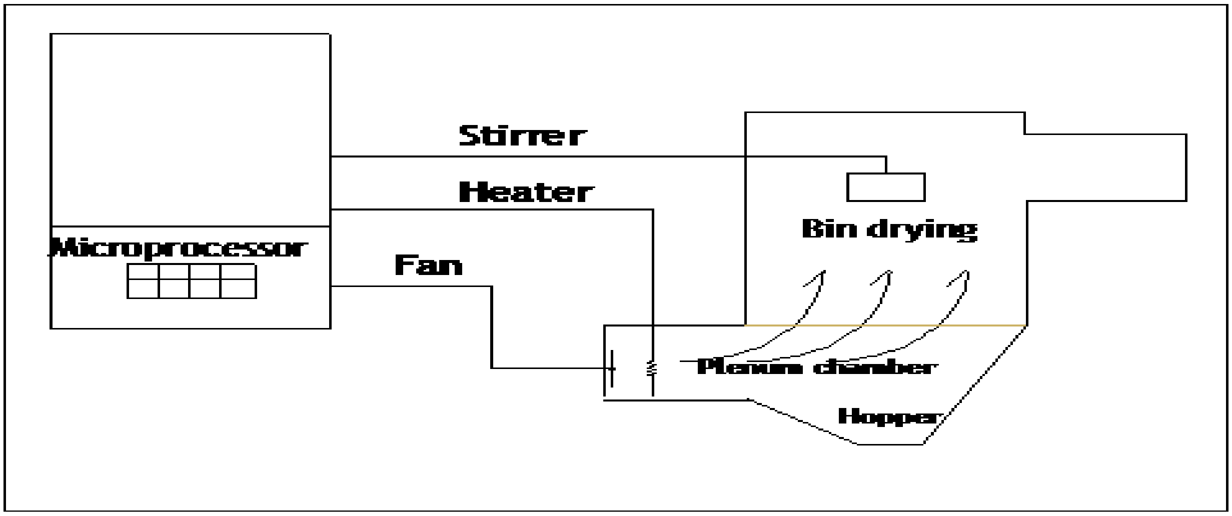

Figure-4
Schematic representation of the drying chamber

Table-3
Simulated and experimental results

Hr	Height	sim-Hum	sim-Mt	sim-Tz	sim –k	exp-Mt	exp-Tz	exp- hum
0	0.03	0.7	16	308.13	0.0000621	16	308.13	0.7
1	0.03	0.7012	15.4	307.03	0.0000619	15.2	307.1	0.7008
2	0.03	0.7021	14.94	306.18	0.0000599	14.75	306	0.7017
3	0.03	0.7028	14.57	305.51	0.0000584	14.44	305.13	0.703
4	0.03	0.7034	14.28	304.98	0.0000573	14.28	304.85	0.7035
5	0.03	0.7039	14.04	304.56	0.0000563	14	304.27	0.7037
6	0.03	0.7042	13.85	304.22	0.0000556	13.92	304.12	0.7038
7	0.03	0.7045	13.7	303.94	0.0000551	13.78	303.98	0.7039
8	0.03	0.7048	13.57	303.71	0.0000546	13.66	303.8	0.7041
9	0.03	0.705	13.47	303.53	0.0000542	13.54	303.62	0.7042
10	0.03	0.7051	13.39	303.38	0.0000539	13.46	303.44	0.7045

Results and Discussion

Simulated and observed results for moisture content: Table 3.0 shows the humidity (hum) moisture content (Mt) temperature (Tz) of both simulated (sim) and experimental (exp) across the grains as the drying proceeds in the chamber. The moisture content of the grain was decreasing with time due to drying of the grain. The dryingwas large enough in the initial phase of drying and small enough in the final phase because of dependence of moisture flow rateon amount of moisture in grain and temperature. The simulated results for the drying process generate a smooth curve that gradually falls whereas the observed values have a bit of variations as seen below. This is due to the environmental conditions at the time of experimentation which varies from the 'ideal' simulated conditions. But generally, the figure shows that there is no significant difference between the observed and simulated moisture contents.

$$y_{act} = 15.44e^{-0.01x} \quad (13)$$

$$y_{sim} = 15.53e^{-0.01x} \quad (14)$$

$$R^2_{act} = 0.898 \quad (15)$$

$$R^2_{sim} = 0.928 \quad (16)$$

Simulated and observed results for temperature: The simulated and experimental drying air temperatures for the drying period of the maize are shown in the figure below. The temperatures are seen to be decreasing due to the loss of heat energy to the grain for the purpose of removing its moisture content. Hence initially it is high but as it makes its way through the layers of grain it reduces gradually as seen. There is generally, good agreement between experimental and simulated temperatures as shown indicating that there is no significant difference between them.

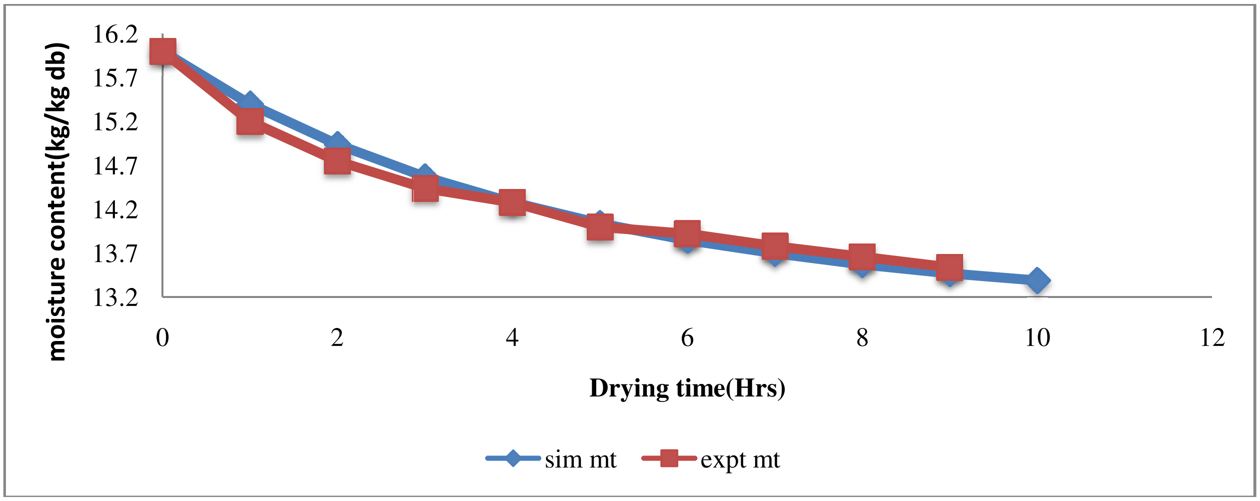

Figure-5
Moisture content curve over time

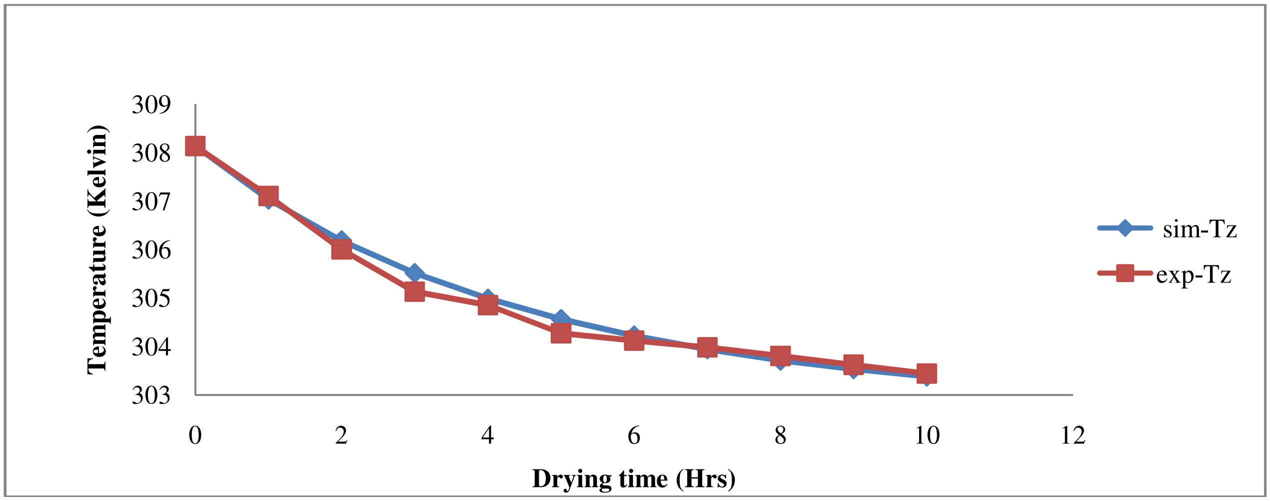

Figure-6
Drying temperature curve over time

$R_{sim}^2 = 0.915$ (17)

$R_{act}^2 = 0.861$ (18)

Simulated and observed results for Humidity: The simulated and observed humidity of the drying air is as shown below. The curve seems to gradually increase with time, this phenomena is so since initially the drying chamberwasmainly occupied initially by very wet grain. As moisture is being removed the drying air absorbs it thereby increasing its humidity content. But after a certain while the absolute humidity tends to be constant because only a small amount of moisture was being removed from the dry grains.

$R_{sim}^2 = 0.929$ (19)

$R_{act}^2 = 0.828$ (20)

Simulated results of different heights: The graph of the behavior of the amount of moisture content of the grains at different drying heights is shown below. It is observed that the amount of moisture removal at different heights reduces as we go up the bin; this is because, as moisture is being removed, the drying air absorbs it thereby increasing its humidity content eventually hampering its capacity to take up more moisture from the grain. Also the temperature of the air reduces as it gives off its heat energy to the grain for the process of drying. This eventually leaves the top most layers ‘wetter’ as compared to the bottom layer.

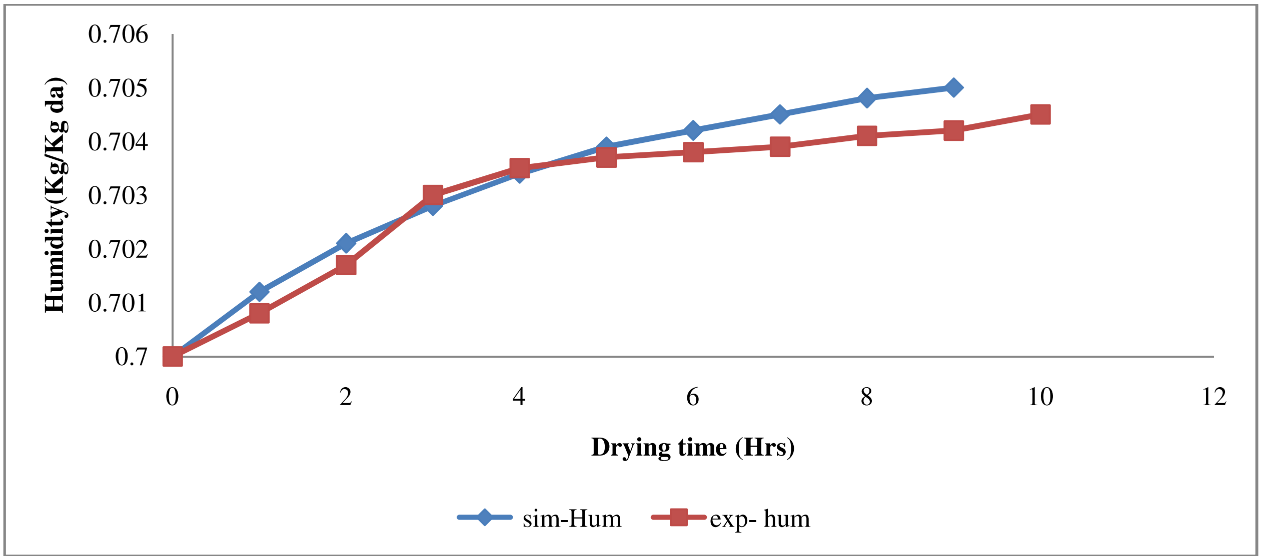

Figure-7
Humidity curve over time

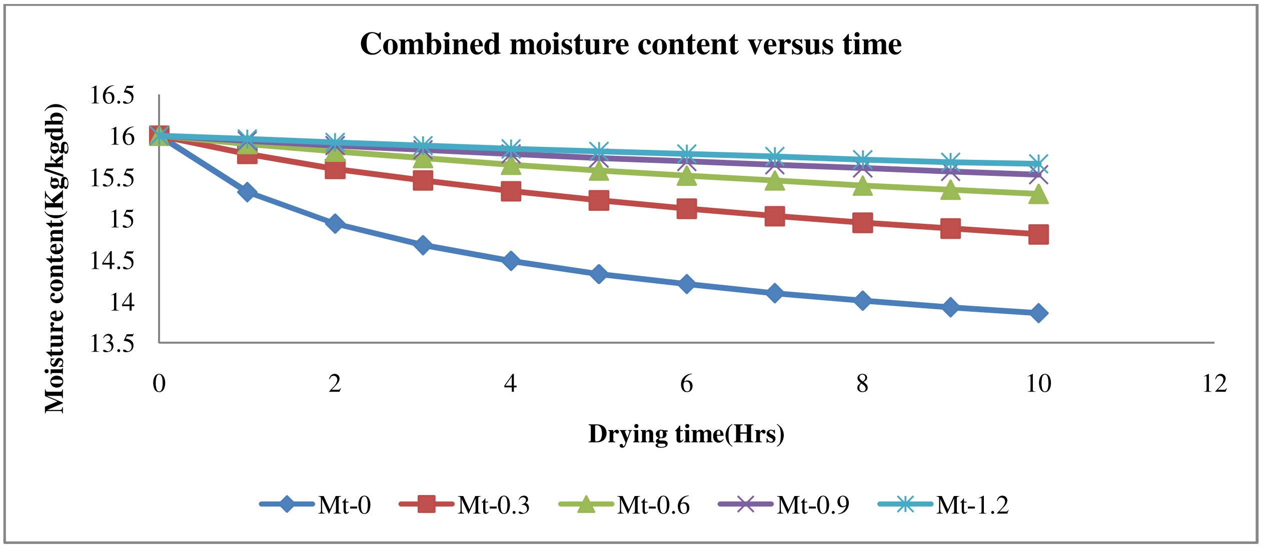

Figure-8
Moisture content curve for different heights

Conclusion

From the results of this study there exist a strong correlation between moisture content and drying time. (R^2=0.929 and 0.894 respectively for simulated and actual data). In addition there is a linear correlation between simulated and experimental moisture content (R^2=0.989). The reduction of moisture content with time was exponential. Besides, temperature and moisture content were reducing with time while air humidity was increasing for both simulated and experimental data. The developed simulation model can be used to predict drying in the automated grain dryer. With the automation of the drying system, controlling of the drying environment is possible, and this minimizes losses and improves storage of the grains.

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