# SIMULATION MODEL FOR PREDICT DRYING IN THE AUTOMATED GRAIN DRYER

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## Abstract

The research was carried out with the objective of developing a simulation model for controlling moisture content and temperature in the grain drying chamber. Mathematical modeling of deep bed grain drying, consisting of three sets of equations- mass balance equation, drying rate equation and energy balance equation was developed. A visual basic computer program was developed to simulate the grain drying. Data simulated by the program was compared with actual experimental data. 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). I n 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.

**Key words:** Grain drying chamber, deep bed grain drying, moisture content, drying time, air humidity

## 1.0 Introduction

Drying is a phase in post harvesting in which moisture content is reduced to a 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 the potential impact of loss causes such as that of premature and unseasonal germination of grain and infestation by insects and fungi (FAO, 1994). Grain in the field dries naturally as the crop matures, giving up moisture to the air until the grain moisture is in equilibrium with the moisture in the air (equilibrium moisture content). Conditions become less favorable for grain to dry to moisture contents considered safe for storage as the harvest is delayed into late fall (Hellevang, 1994).This has led to the use of mechanical driers which are not efficient due to 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 in which 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, since the difference between the dew point temperature of the input air 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, since the Grain moisture content affects the quantity and quality of grain, price discounts and premiums, as well as grain storability, the moisture content may affect 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; Lastly storage life which indicates the length of time grain can be stored without significant deterioration is determined by temperature and the moisture content at which it is stored. In order to obtain the 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 the model, we relied on the work of several authors who have developed simulation models for analysis of deep bed grain drying. These include Sitompul, *et al*., (2002), Aregba-Driollet *et al*.; (2006). In addition, we also considered related studies on Simulation of natural air drying of maize in cribs carried out by Bala, *et al*., (2003). We however established that no studies have been carried out aimed at simulation of mechanical grain drying where a fan and heater are used.

Based on these facts, the study proposed a Simulation model designed to use humidity and temperature to simulate the 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.

## 2.0 Materials and Methods

### 2.1. Description of the Experimental Site

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

### 2.2 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 done 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 were undertaken to ensure 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 make it suitable for outdoor operation. It was 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 was further away from the grain to reduce the chances of grain lift off especially the light grains. Discharge was done through the hopper. Figure 1 shows the drying chamber system.

*Figure 1: Grain drying chamber*

### 2.3 Grain Drying Model

Drying is an operation which involves simultaneous heat and mass transfer. The physical mechanism of drying in hygroscopic-porous products such as corn grain is quite complicated. It is generally agreed that the moisture within grain moves in the form of a liquid and/or vapour. A number of physical mechanisms have been proposed to describe the transfer of moisture in products. The model development of deep bed dryer follows a simple analogy as described below. Consider a bed of grain of cross sectional area *A* and height *L* whose elemental layer is as depicted in Figure 2. The conservation equations are written over elemental control volume over unit cross section and of height *z*. The liquid movement can be due to surface forces (capillary flow), moisture concentration differences (liquid diffusion), diffusion of moisture on the pore surface (surface diffusion), while vapour movement can be due to moisture concentration differences (vapour diffusion), temperature differences (thermal diffusion) and water and vapour movement due to the total pressure differences (hydrodynamic flow) (Brooker *et al.,* 1978). Figure 2 demonstrates this analogy.

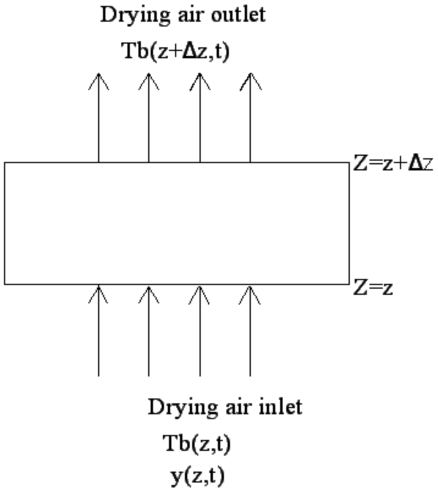

*Figure 2: Elemental bed of corn grains*

There are several assumptions applicable in analysis of the deep bed drying (Garg and Prakash, 2000; Bala, 1997; Dimitriadis and Akritidis, 2004) which include the fact that: no shrinkage occurs during drying; air flow is restricted to a uni-directional in the x and y directions respectively; in the drying chamber thermal conduction between two grain particles is negligible and no conductive heat losses within the drying bed; within an individual particle, temperature gradient is negligible; the dryer walls are adiabatic, and have 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 collector, other than heat loss calculable through overall heat loss coefficient, uniform grain kernels 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 surface moisture content takes a volume of dynamic equilibrium moisture content. The analysis of drying in a deep bed would include 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 the air and raise its temperature expressed by model equation 1:

$$\mathrm{Q} = \dot{\mathrm{m}}_{\mathrm{a}}\left(\mathrm{C}_{\mathrm{pa}} + \mathrm{HC}_{\mathrm{pv}}\right)(\mathrm{T} - \mathrm{T}_{\infty}) \text{……………………………………………………………………………………………………} \quad (1)$$

In the bin there are four types of processes taking place as illustrated by model equations 2 to 5.

i. The rate of incoming hot air is losing its heat at a rate given by: $\dot{\mathrm{M}}_{\mathrm{a}}(\mathrm{C}_{\mathrm{pa}}+\mathrm{C}_{\mathrm{PV}}\mathrm{H})\ \Delta\mathrm{T}_{\mathrm{a}}$……………………… (2)

ii. The grain gains heat at a rate given by: $\mathrm{mg}(\mathrm{c}_{\mathrm{pg}}+\mathrm{c}_{\mathrm{pw}}\mathrm{m})\ \frac{\partial \mathrm{T}_{\mathrm{g}}}{\partial \mathrm{t}}$ …………………………………………………………… (3)

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

iv. 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)

## 2.4 Mass Balance

The change of humidity in the drying chamber is given by model equation 6 and 7 (Bala, 1997, Dimitriadis and Akritidis, 2004; Garg and Prakash, 2000; Garreiro et al., 2006)

$$\frac{\Delta H}{\Delta Z} = -\frac{\rho \partial M}{G_a \partial t} \quad \text{………………………………………………………………………………………………………………………… (6)}$$

The flow rate is evaluated from

$$G_a = \frac{\dot{M}_a}{A} = \rho_a V_a \text{…………………………………………………………………………………………………………………………(7)}$$

The humidity generation in the drying chamber can be analyzed by Equation 6, in which as the humidity in the chamber increases towards saturation vapour 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 vapour pressure due to the moisture evaporated from the drying grain must never exceed the saturated vapour pressure. In order to monitor the contribution of humidity on the drying process, it was necessary to evaluate the vapour pressure against saturation vapour pressure. Tiwari *et al*. (2006) gave the properties of drying air as in Table 1, in which $\rho_v$ is the density of drying air (kg/m$^3$), P(T) the partial vapour pressure (Pa) at temperature T (K).

*Table 1: Properties of drying air*

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

Source: Tiwari *et al.,* (2006)

The saturated vapour pressure $P_s$ (Pa) at temperature T (K) is derived from the model Equation given by (Hahn, 1990) as

$$P_s = R_s \left( \exp\left( \frac{A_s + BT_a + CT_a^2 + DT_a^3 + ET_a^4}{FT_a - GT_a^2} \right) \right) \quad \text{……………………………………………………………………………… (8)}$$

The parameters in model Equation 8 were as presented in Table 2.

*Table 2: 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)

The last Equation in Table 1.0 and Equation 8 are useful in evaluating the vapour pressure against saturation vapour pressure.

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

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

## 2.5 The Drying Rate Analysis

The drying rate equation for thin layer drying is expressed as in model equation 10 (Bala, 1997; Garg and Prakash, 2000; Kajuna *et al*., 2001; Joshi *et al*., 2005; Phoungchandang and Woods, 2000; Kribs and Spolek, 1997)

$$\frac{\partial \text{M}}{\partial \text{t}} = -k(M - M_e) \quad \text{…………………………………………………………………………………………………………………………(10)}$$

Model Equation (8) can be evaluated with its boundary conditions as in model equation 11 (Sitompul et al., 2001, Garreiro et al., 2006; Singh and Gupta, 2007; Srivatsava and John, 2007, Rahman and Kumar, 2007):

$$\begin{Bmatrix} M(t_0, \mathrm{u}) = M_0 \\ M(t_e, u) = M_e \end{Bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(11)}$$

The Newton's solution model to Equation 8 is expressed as (Bala, 1997; Kadam and Samuel, 2006; Jian and Pathare, 2007)

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

## 2.6 Data Acquisition and Model Performance

### 2.6.1. Simulation Algorithm

A visual basic 6 algorithm was developed to model the drying process based on the flowchart below and equations 1 to 11. The input parameters included grain temperature, grain moisture content, input air temperature and grain storage life. A flow chart for the simulation process was as shown in Figure 3.

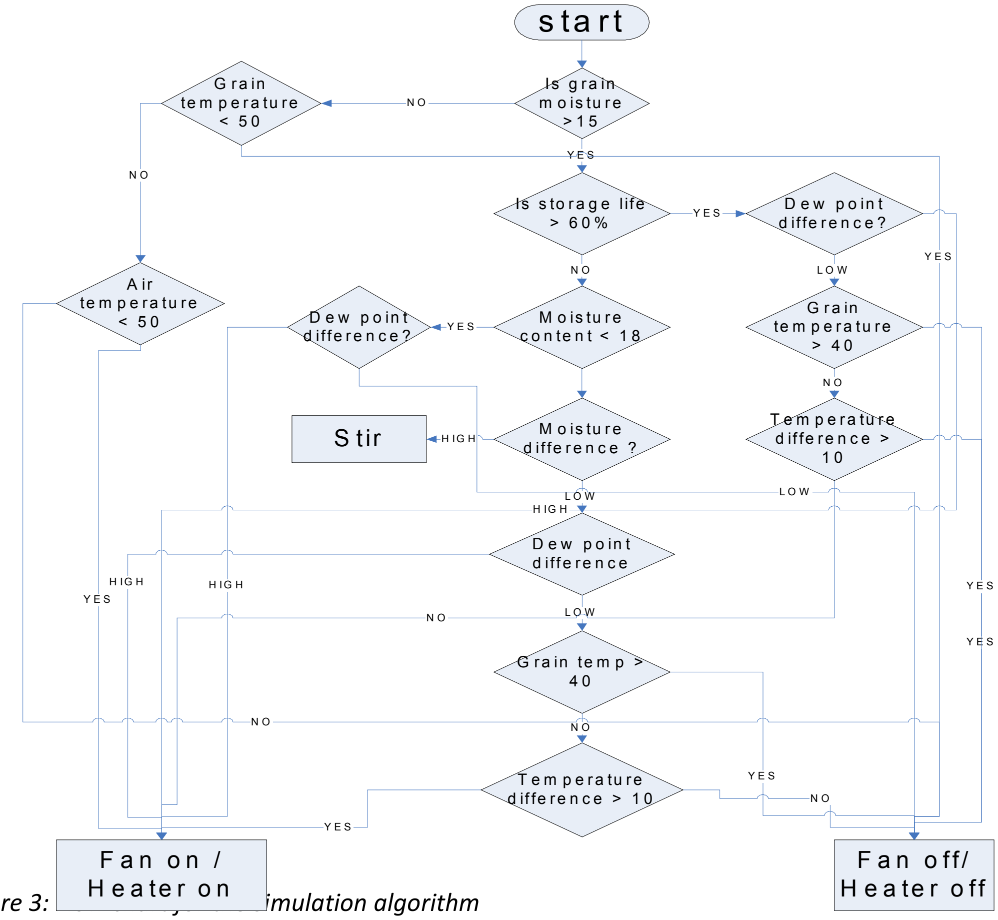

*Figure 3:* *imulation algorithm*

### 2.6.2. Experimental Set-Up

Figure 4 presents a schematic diagram of 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 at an interval of an hour for ten hours. The flow rate of 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.

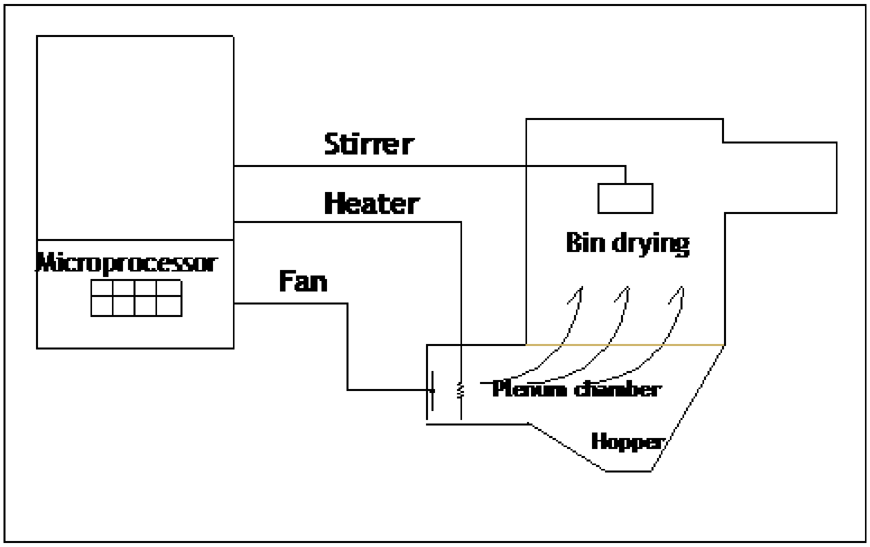

*Figure 4: Schematic representation of the drying chamber*

## 3.0 Results and Discussions

The results of the simulated and experimental observations as recorded during the experiment are summarized in Table 3.

*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 |

### 3.1 Simulated and Experimental Results for Moisture Content

The figure shows the average moisture content across the grains as the drying proceeds in the chamber. The moisture content of the grain is decreasing due to the removal of the moisture from the grain. The moisture removal is large enough in the initial periods of drying and small enough in the end periods because of moisture diffusivity dependence on grain moisture content and temperature. The simulated results for the drying process generate a smooth curve that gradually falls whereas the experimental 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 experimental and simulated moisture contents.

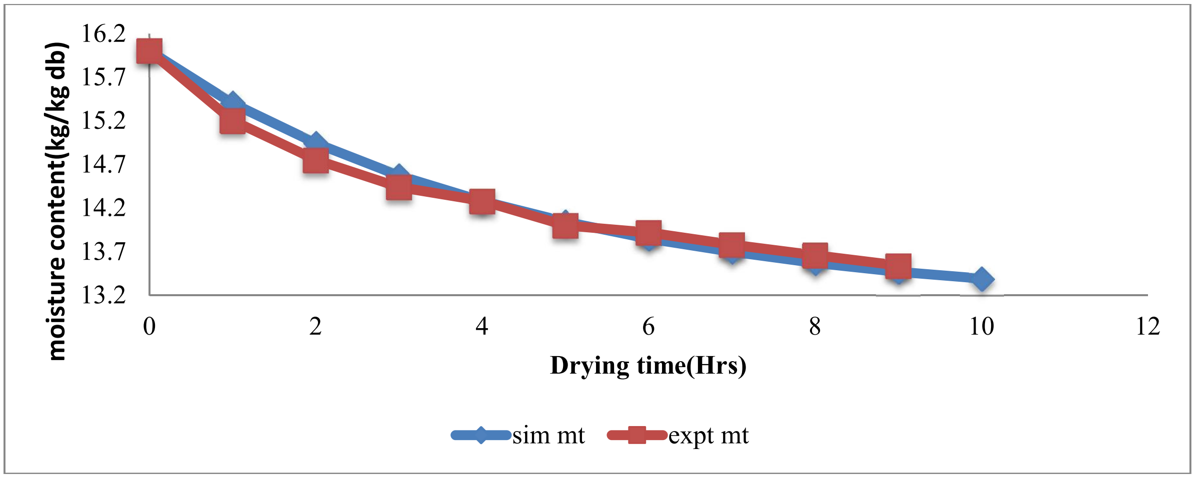

*Figure 5: Moisture content curve over time*

$y_{act} = 15.44e^{-0.01x}$ …………………………………………………………………………………………… (12)

$y_{sim} = 15.53e^{-0.01x}$ …………………………………………………………………………………………… (13)
$R^2_{act} = 0.898$ ……………………………………………………………………………………………………(14)
$R^2_{sim} = 0.928$ ……………………………………………………………………………………………………(15)

### 3.2.1 Simulated and Experimental 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 in curve. As observed, there is no major observed difference between the experimental and simulated temperatures.

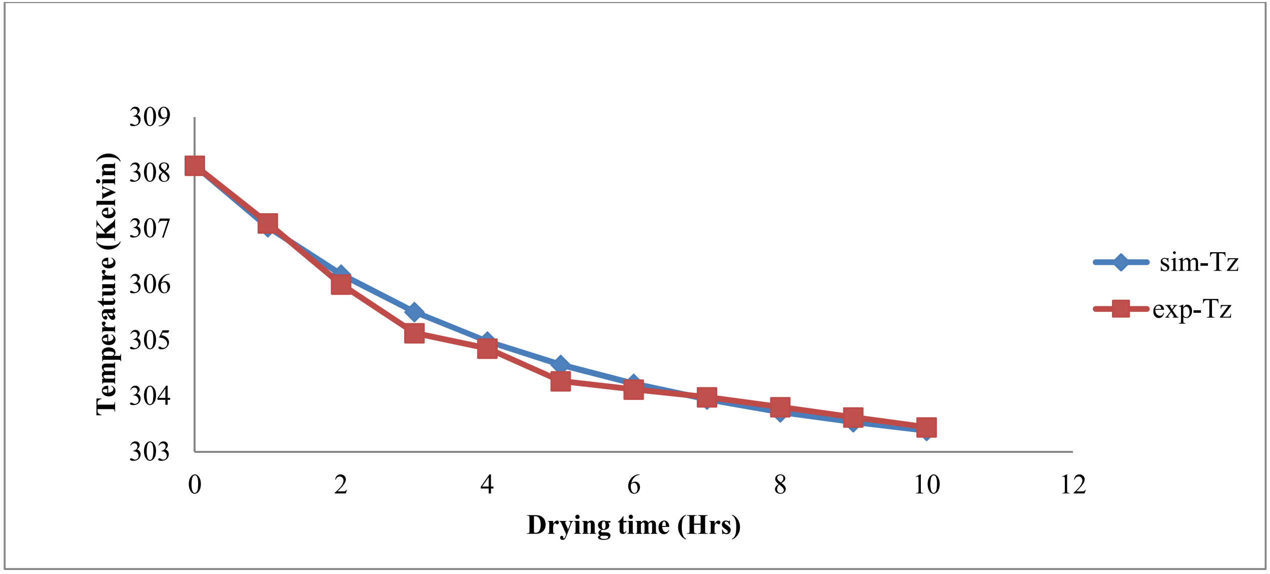

*Figure 6: Drying temperature curve over time*

$R_{sim}^{2} = 0.915$ ……………………………………………………………………………………………………………………………(16)
$R_{act}^{2} = 0.861$…………………………………………………………………………………………………………………………(17)

### 3.3 Simulated and Experimental Results for Humidity

The simulated and experimental humidity of the drying air are as shown below. The curve seems to gradually rise with time, and this phenomenon is so since initially the bed is predominantly occupied by initial wet grain with large enough moisture to be removed. As moisture is being removed the drying air absorbs it thereby increasing its humidity content. But after a while the absolute humidity tends to be constant since only a little moisture is removed from the dried grains.

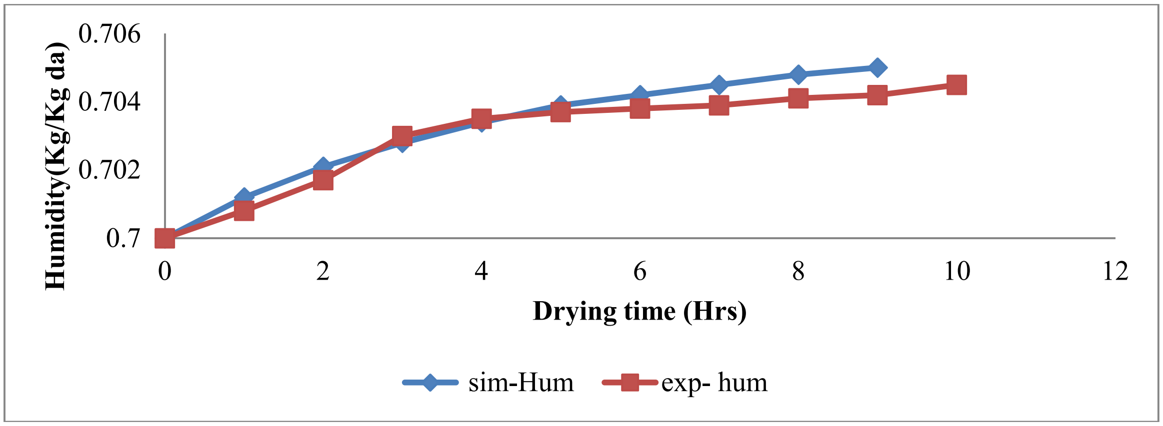

*Figure 7: Humidity curve over time*

$R_{sim}^{2} = 0.929$ ……………………………………………………………………………………………………………………………(18)
$R_{act}^{2} = 0.828$ ……………………………………………………………………………………………………………………………(19

#### 3.4.1 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.

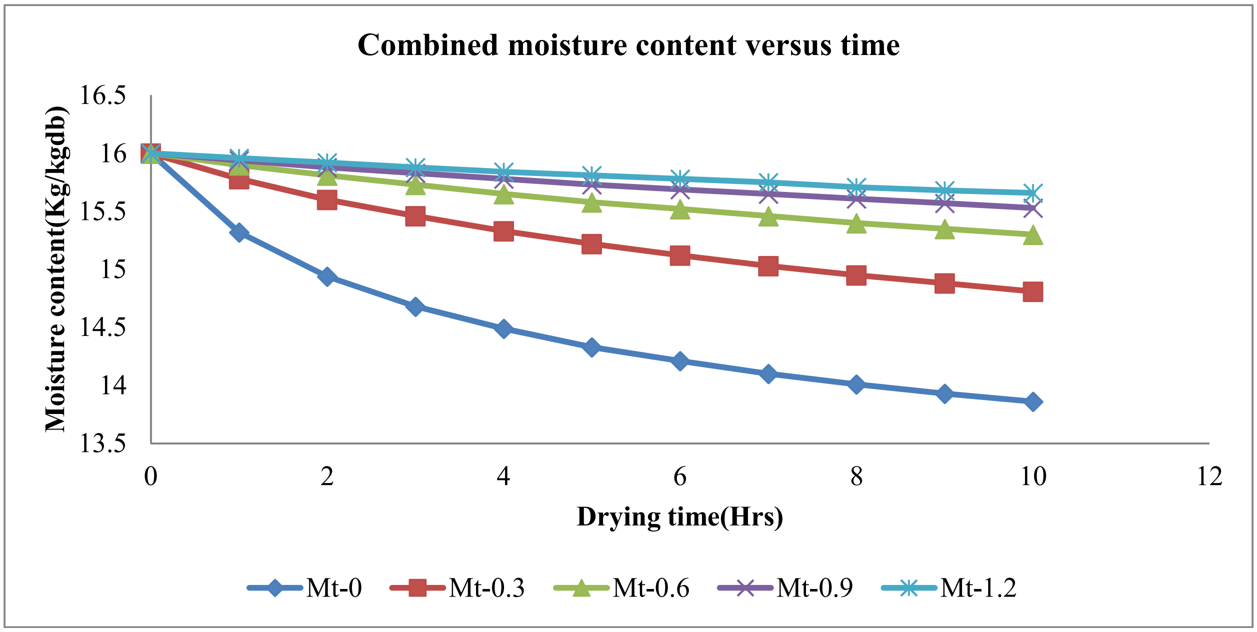

*Figure 8: Moisture content curve for different heights*

## 4.0 Conclusions and Recommendations

The results of this study show that 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 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.

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