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EFFECTS OF NON-UNIFORM AIRFLOW DISTRIBUTION ON GRAIN MOISTURE CONTENTS DURING AERATION

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ABSTRACT

Maintaining the quality of grains in storage over long periods of time is dependent on several factors, including the provision of a functional aeration system and an adequate management strategy. The growth and activities of insects in stored grains is a function of time, grain moisture content and grain temperature, but this can be controlled with effective aeration. To ensure effective aeration the conditions of the grains in storage must be monitored. Though several models exist for the prediction of grain moisture contents during aeration, most of these models assume airflow to be uniform during aeration. Thompson's model which is commonly used for predicting grain moisture content assumes uniform airflow during aeration. Conversely, airflow is non-uniform in hopper bottom silos and partially perforated floors. Therefore the objective of this study is to modify Thompson's model used for natural drying so it could be used to predict the moisture contents of grains during aeration when non-uniform flow of air is considered. A hopper bottom silo of 3m radius filled to a grain height of 1.8m was used for this study. Four tests, each test under different testing conditions and lasting 120 hours, were carried out to investigate the non-uniform movement of air. The investigations revealed that the modified model presented in this study is useful for predicting moisture content to within 0.5% of measured moisture content when non-uniform airflow is considered. The coefficient of determination (R^2) between the measured and predicted values obtained for the moisture tests ranged from 0.97 to 0.98.

Keywords: grain, aeration, non-uniform, hopper bottom.

INTRODUCTION

Airflow distributions in most grain structures is non-uniform due to the variations in material properties of the grain mass, the geometry of the storage structure and/or the design of the aeration system. Airflow is generally assumed to be uniform in silos with fully perforated floors and non-uniform in silos with aeration ducts, pads or partially perforated floors. The airflow distribution can also be non uniform in a silo with hopper bottom, peaked grain from overfilling, inverted grain from partial uploading and high fine material concentration in the core of the grain mass (Bartosik and Maier, 2006).

According to Garg and Maier (2006), one of the primary causes of non uniform airflow distribution is variation in the material properties of the grain mass. Airflow resistance is a function of particle size and porosity of the grain. Therefore a number of material properties like the distribution of fine material, the loading method, moisture content and level compaction cause non uniform airflow distributions.

Several investigators have investigated the non-uniformity of airflow and resistance in a grain mass; however the investigators focused on developing models to calculate pressure drop and consequently power consumption by aeration fans. Little has been reported on the effects of non-uniformity of airflow on moisture content.

Ergun (1952) presented an equation to calculate the pressure drop of fluid flow based on Reynolds Theory. According to this equation, the total energy loss in a packed bed is the sum of the viscous and kinetic energy losses. Ergun's equation has been modified by several investigators to model non-uniform airflow. Lai (1980) investigated three-dimensional axisymmetric (3D) non-uniform airflow in cylindrical grain beds. According to Lai (1980), the porosity of grains differs at different locations within the bin and therefore he divided the grain mass into two regions with different porosities (0.4 at the centre and 0.6 at the periphery). He then used Ergun's equation to calculate the resistance to airflow. Smith (1996) modified Ergun's (1952) non nonlinear momentum equation into curvilinear coordinates and used it to predict the pressure drop through a grain mass. Garg and Maier (2006) modified Ergun's (1952) equation and inserted it into FLUENT (a Computational Fluid Dynamics software) to model non-uniform airflow distribution in large silos. The modified Ergun's equation was applied to three scenarios: a peaked grain mass, a grain mass with a high fines concentration core, and a grain mass aerated from a ring duct around the bottom of the silo wall. They reported that non-uniform airflow resulted in the reduction of air velocity and volumetric airflow rate within grain layers during aeration. However, the model was not validated with measured data.

Hukill and Shedd (1955) presented a model to predict the pressure drop over an airflow range between 0.01-0.20 $m^3/s\ m^2$. The American Society of Agricultural and Biological Engineers (ASABE) modified Shedd's equation and approved it for determining the static pressure drop of airflow through a grain bed (ASABE Standards, 2006)

Kay *et al.* (1989) investigated airflow resistance in corn grains and reported that the horizontal airflow resistances through corn grains were about 58 and 45% of the vertical airflow resistance when airflow rates were above and below 0.lm^3/s m^2, respectively.

Garg (2005) investigated the heat and mass transfer due to non-uniform airflow distribution in a grain

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mass in two dimensions. He used Lai's (1980) variable concept to develop a non-uniform airflow model for stored grain. Two different porosities, one for the centre core volume and the second for the periphery were used. He then used FLUENT and 2D PHAST-FEM (Post-Harvest Aeration and Storage Simulation Tool developed at Purdue University) to simulate the heat and mass transfer.

Bartosik and Maier (2006) studied the non-uniform airflow distribution in cored, peaked, and leveled grain mass. They measured airflow at the periphery and centre for each grain mass within a bin. A non-uniformity factor (NUF) which was defined as a function of the difference in average airflow rate at the centre versus periphery was used to model non-uniform airflow.

Lawrence and Maier (2011) used a 3D airflow model to investigate the non-uniform airflow in leveled, peaked and inverted cone grain mass. They used two constant porosities (0.38 and 0.40) and three variable porosity ranges (0.34-0.38, 0.36-0.38, and 0.38-0.40) for corn to validate the airflow distribution. They reported that for the variable porosity of 0.34-0.38 the model predictions closely followed the experimental results.

As air moves upstream in bin during aeration, initial volumetric airflow rate of the air is reduced. The reduction in volumetric airflow rate is largely influenced by the geometry of the grain bin and the porosity of the grains. The volumetric airflow rate at the floor entry of the bin differs from the volumetric flow rate at other positions within the bin especially, when hopper bottom silos and silos with aeration ducts above the floor are used. The volumetric flow rate therefore becomes non-uniform at different layers within the grain mass.

This study seeks to investigate the effect of reduction in the initial volumetric airflow rate on grain moisture contents due to non-uniform air flow.

MATERIALS AND METHODS

Data collection

Four aeration tests were conducted to collect data for the validation of the modified model (Equations 8). Each test lasted for a continuous period of 120 hours.

For each test, approximately 7059 Kg (7.059 tonnes) of corn stored in a steel hopper bottom silo located at Anloga (in the Volta Region of Ghana) was used. The silo was equipped with 0.37kW fan and also with perforated air distribution ducts of 0.125 m (5 inches) in diameter, arranged in a ring type to a total circumferential length of approximately 6m. This arrangement gives a total duct surface area of 1.89 m^2. Perforations on the ducts were approximately 40% of the total ducts surface area. This gives the perforated floor area (F_A) of 0.756m^2.

The bin was filled to a height of 1.8m of the grain level and the topmost surface of the grain leveled to avoid peaking of grains at the surface. A total grain depth of 1.5m was probed to determine moisture content and temperature changes. Probing was carried out at grain intervals (depth) of 0.5m. The bottom layer was taken as Layer one, the middle layer as Layer two and the top layer as Layer three. After every 24 hours, grains were sampled for moisture content determination. The grains were sampled from five sample points in each layer according to standards presented by Loewer *et al*., 1994. Initial airflow rates, ranging from 2 $m^3min^{-1}m^{-2}$ to 5 $m^3min^{-1}m^{-2}$ (0.2 $m^3min^{-1}tonne^{-1}$ to 0.5 $m^3min^{-1}tonne^{-1}$) were used for the four tests (Table-1).

Table-1. Test conditions under which aeration was conducted.

Test Condition	Test 1	Test 2	Test 3	Test 4
	November 12-16, 2012	November 19-23, 2012	November 26-30, 2012	February 7-11, 2013
Average initial grain moisture content (%WB)	17	18	19	20
Initial airflow rate ($m^3min^{-1}m^{-2}$)	2	3	4	5
Average initial ambient air temperature (^oC)	27.7	28.4	28	28.6
Initial grain temperature (^oC)	28.2	29.2	28.9	29.4
Average initial relative humidity (%)	77.8	77.7	73.3	78.9
Initial absolute humidity (kg water/kg of dry air)	0.0154	0.0154	0.0154	0.0154

Thompson's model

Thompson 1972 presented Equation (1) for predicting the average moisture content of grain within a grain layer. Thompson's model has a long successful history of being used to predict moisture contents of grains accurately within a uniform airflow bin However. Thompson's model can be modified to predict the moisture contents of grains when airflow is non-uniform.

$$H_f - H_o = \frac{(M_o - M_f)R}{100} \quad \text{Kg Water/Kg Dry air (1)}$$

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From Equation (1)

$$M_f = M_o - \frac{100 \times \Delta H}{R} \tag{2}$$

$$\Delta H = H_f - H_o \tag{3}$$

Mo = Initial moisture content (%)
M_f = Final moisture content (%)
H_o = Initial absolute humidity (Kg/Kg of dry air)
H_f = Final absolute humidity (Kg/Kg of dry air)
H = Change in absolute humidity (Kg/kg of dry air)
R = Dry matter to air ratio (Kgm^{-2}/Kgm^{-2})

Modifications made to Thompson's models

To calculate the final moisture content, Thompson (1972), used the dry matter to air ratio (R) as an input parameter (Equation 6). This input parameter can be expressed mathematically and modified to calculate the contribution of non-uniform movement of air to changes in moisture content. Mathematically, the dry matter ratio can be derived as;

$$R = \frac{\rho_{dm} X}{\Delta t \times V \times \frac{60}{V_s}} \tag{4}$$

According to Al-Yahya (1996),

$$V_s = 0.0252 \times (To + 460) \times (1 + 1.6055 \times H_o) \times 0.063 \tag{5}$$

Where

ρ_{dm} =	Bulk density of grain	(kg/m^3)
X =	Grain layer thickness (depth)	(m)
Vs =	Specific volume of air	(m^3/kg)
Δt =	Time interval	(hours)
V =	Volumetric flow rate	$m^3min^{-1}m^{-2}$
T_o =	Initial air temperature	(^oC)

60 is a conversion factor for Δt, from hours to minutes.

Non-Uniform movement of air

The mathematical relationship between the initial volumetric flow rate U_a ($m^3min^{-1}m^{-2}$) and the effective volumetric flow rate V ($m^3min^{-1}m^{-2}$) within the layers of the grain can be used to calculate the reduction in the initial volumetric flow rate. The effect of the reduction in the initial volumetric flow rate on moisture content of grains during aeration can then be determined. The mathematical relationship for this action can be derived as:

$$V = \left(1 - \frac{F_A}{\varepsilon . L_A}\right) U_a \tag{6}$$

Where

U_a = Initial volumetric flow rate at the floor/duct entry ($m^3min^{-1}m^{-2}$)
V = Volumetric flow rate at a specified point within the silo other than entry ($m^3min^{-1}m^{-2}$)
L_A = Area occupied by grain layer (m^2)
F_A = Perforated floor area (m^2)
ε = Grain Porosity (Dimensionless number factor)

Each layer of the grain is considered to occupy a specific area (L_A). Therefore the area available for the air to move within the grain in each layer can be obtained by multiplying grain layer area (L_A) by the grain porosity (ε).

The Perforated floor area (F_A) is the total open or perforated area available on the surface area of the ducts for the air to emerge from the ducts into the silo. Duct surface area can be obtained by using the Table provided by Noyes (1967). The perforated floor area (F_A) can then be calculated by multiplying the percentage of duct perforations on the duct surface area with the total duct surface area.

Substituting Equation (6) into Equation (4) gives Equation (7)

$$R_{fn} = \frac{\rho_{dm} X}{\Delta t \times \left(1 - \frac{F_A}{\varepsilon . L_A}\right) U_a \times \frac{60}{V_S}} \tag{7}$$

Where R_{fn} = Dry matter to air ratio in a given layer.
Inserting Equation (7) into Equation (2) gives

$$M_{fn} = M_o - \frac{100 \times \Delta H}{\frac{\rho_{dm} X}{\Delta t \times \left(1 - \frac{F_A}{\varepsilon . L_A}\right) U_a \times \frac{60}{V_S}}} \tag{8}$$

The modified model (Equation 8) can be used to predict the moisture contents within a grain layer when hopper bottom silos and silos with aeration ducts above the floor are used.

The principles of deep bed simulation were employed to develop a computer simulation program for predicting moisture contents. The simulation program was developed using Visual Basic Editor in Microsoft Excel. Grain thickness (depth) of 0.05m, time increment of 8 hours, bulk density of $720kg/m^3$ according to ASABE standards (ASAE, 1998), whiles an average grain mass per simulated layer of 2000kg, porosity of 0.38 and perforated floor surface area of $0.756m^2$ were used as fixed values in the computer program. During the simulation process, the grain moisture content was calculated for each layer in an iterative way.

The term which describes the properties of the aeration air (the second term at the right hand of Equation 8) was programmed to run iteratively. The value from the iteration at a particular layer was then subtracted from the

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initial moisture content of the grain at that layer to give the final moisture content at that layer. The exhaust air from the previous layer was programmed to be the input air for the subsequent layer. This process was repeated until the iteration reached the grain height of 1.5m.

RESULTS AND DISCUSSIONS

To determine the correlation between predicted values and measured values, a scatter plot was developed for each test and the coefficient of determination (R^2) determined. According to *Loewer et al.* (1994), a very good model has an R^2 value equal to or greater than 0. 95.

A single factor analysis of variance (ANOVA) was made for each test to determine the significance of variations between the predicted and the measured results. At the confidence interval of 95%, the null hypothesis employed was that, significant variations exist between the predicted and measured value If the P value computed is less than or equal to 0.05 or if the F value value computed is greater than or equal to F critical value ($P_{value} \leq 0.05$ and $F \geq$ Fcit, respectively) then there is a premise to reject the correlation between predicted and measured values must be rejected.

Accuracy of prediction was determined by observing the error difference. For each test, average absolute error and standard error was calculated to determine errors between predicted and measured moisture contents. The average absolute error was calculated using Equation (9) while standard error was calculated using Equation (10).

$$AAVR = \frac{\sum|(Y - Y')|}{obs} \quad (9)$$

$$S.E = \frac{\sum(Y - Y')^2}{df} \quad (10)$$

Where

AAVR = average of the absolute value of the residuals.
Y = measured value
Y´ = value predicted by the model.
obs = number of observations.
S.E. = standard error of the residuals.
Y = measured value
Y´ = value predicted by the model.
df = degree of freedom (n-1).

Figure-1 through to Figure-4 show the moisture content results for the four tests.

The results from the prediction equation are shown with "P" attached to their labels whiles the measured results have "M" attached to their labels.

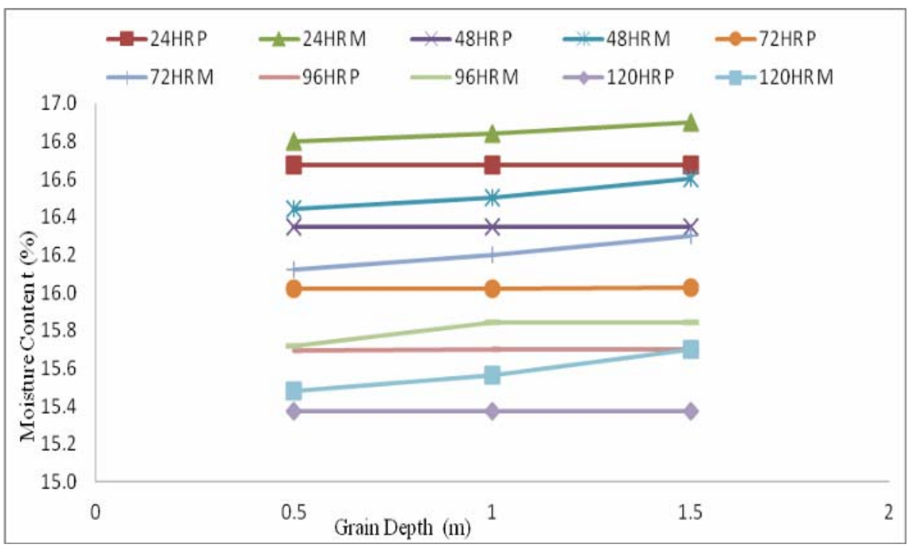

Figure-1. Predicted and Measured Moisture Contents recorded at different grain depths and aeration hours during Test 1.

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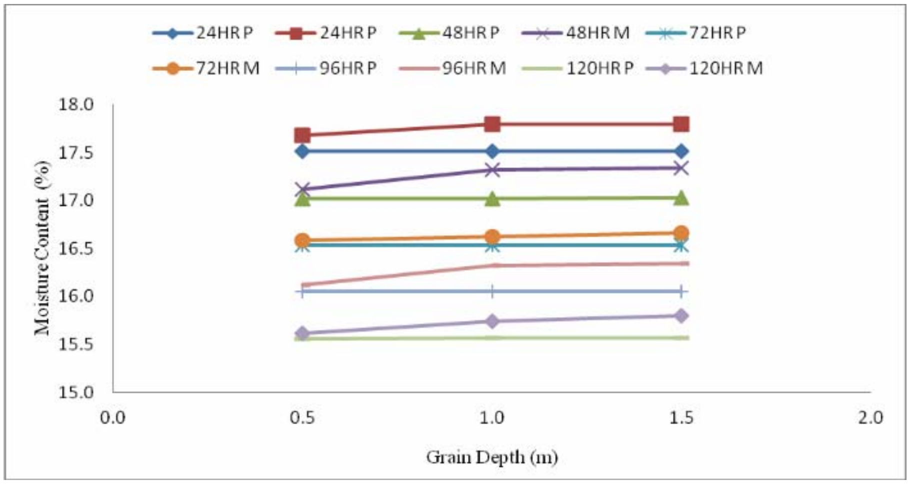

Figure-2. Predicted and Measured Moisture Contents recorded at different grain depths and aeration hours during Test 2.

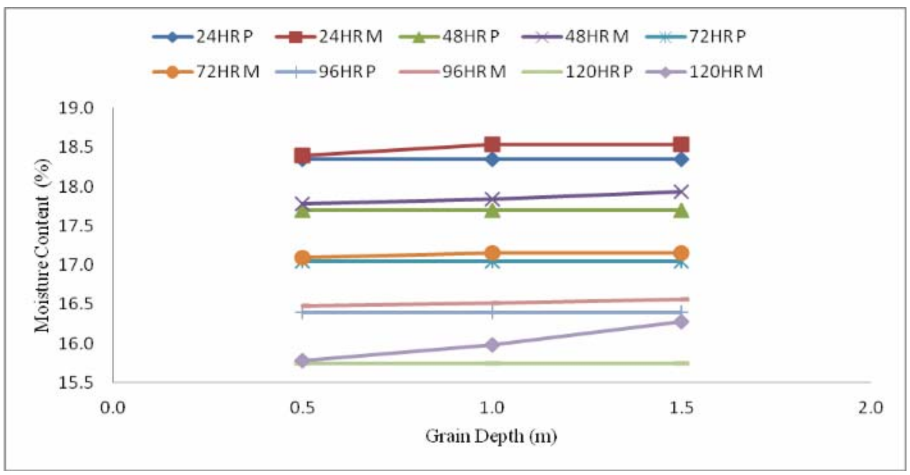

Figure-3. Predicted and Measured Moisture Contents recorded at different grain depths and aeration hours during Test 3.

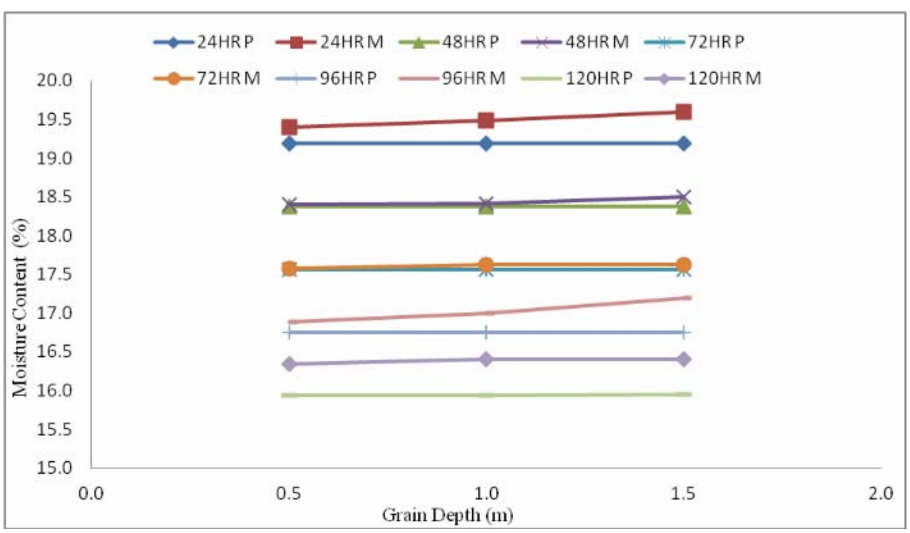

Figure-4. Predicted and Measured Moisture Contents recorded at different grain depths and aeration hours during Test 4.

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The predicted values were numerically lower than measured values for all tests at each grain depth and for all time intervals (Figures 1 to 4). This implies that the modified model (Equation 18) presented in this work removes a greater amount of moisture than the actual aeration process. However, the amount of moisture removed by the modified model is less than that removed by the original Thompson model (Equation 6). The term (Equation 6) which was inserted into the original Thompson (1972) model reduced the volumetric flow rate used for aeration at each layer. A reduction in the volumetric flow rate increased the dry matter to air ratio (Equation 7). Consequently, an increase in the dry matter to air ratio resulted in lesser amount of moisture being removed. The lesser amount of moisture removed minimized under prediction. The modified model presented in this work therefore reduced the extent of under prediction as compared to the original Thompson (1972) model.

Average absolute error and the standard error of the residuals for all tests were within 0.5%. The analysis of variance made for each test shows that at the 95% confidence interval, there were no significant variations between the predicted and measured moisture content.

The results obtained from this study agree with the hypothesis made by Garg and Maier (2006) that non uniform motion of air results in reduction of volumetric airflow rates among grain layers.

CONCLUSIONS AND RECOMMENDATION

The modified Thompson model (Equation 8) presented in this work is useful for predicting the moisture content among grain layers to within 0.5% of actual moisture contents of grains in a silo when a reduction in the initial airflow rate due to non-uniform motion of air is considered.

The modified model presented in this work under predicted moisture content values because rewetting of the grains may have occurred. It is therefore recommended that a modified a term that calculates for rewetting can be developed in subsequent studies.

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