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Research Paper

Moisture diffusion simulation through wheat stored in a metallic silo

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ABSTRACT

The objectives of the study were to test a mathematical model to predict moisture contents within wheat stored in a cylindrical metallic silo and to verify the tested model by comparing the experimental moisture values with the predicted ones. The tested finite difference model was used to simulate moisture diffusion in both the radial and vertical directions in the silo. The model predicted grain temperatures and moisture contents in the silo using input data of initial grain temperature, initial grain moisture content, ambient air temperature, storage time, number of spatial elements in both directions, finite difference spatial increment in both directions and thermo-physical properties of grain and silo wall material. The experimental data was collected during the period of 91 days. Results showed that under the storage conditions moisture diffusion took place within the stored wheat in the silo. The tested model predicted wheat moisture content accurately and within the bounds of the experimental error. The standard error of estimate between measured and predicted moisture contents was 0.29 to 0.59% (w.b.). It was also found that Chung's sorption equation was satisfactory in simulating the moisture contents within wheat bulk stored in the metallic silo. Computer simulation of moisture contents and temperatures of stored bulk grain to monitor safe storage conditions could be opted as reliable, inexpensive and a fast technique.

Key words: Moisture diffusion, simulation, finite difference, wheat, silo.

INTRODUCTION

Wheat is the second major staple food, after corn, for billions of people worldwide. Wheat provides a large proportion of the daily energy intake and represents a healthy source of multiple nutrients, dietary fibre and bioactive compounds, especially if consumed as a whole-grain (Dinu et al., 2018). In 2016, the top 10 wheat producing countries were China, India, Russian Federation, United States of America, Canada, France, Ukraine, Pakistan, Germany and Australia, whereas in 2016, wheat imports of Kingdom of Saudi Arabia were 3576571 tonnes (FAOSTAT, 2018). Of the numerous structures used for storing wheat are the grain silos constructed from different building materials. In normal storage conditions, moisture content and temperature are the two abiotic factors that affect the distribution and abundance of insects and fungi, which contaminate the stored grain (Xanthopoulos and Woods, 2003).

Experimental studies of moisture distribution are laborious, expensive, time intensive and can yield only specific information related to the local experimental conditions. In addition to this, lack of reliable moisture sensors makes the field studies of moisture distribution very difficult. In such a situation, mathematical models based on transport principles are useful and inexpensive tools to predict the potential spoilage of stored grains, in comparison to the high cost and time consuming operation of continuous temperature monitoring and grain moisture content probing (Gaston et al., 2009). Hence, the use of mathematical models to predict grain moisture content and temperature evolution constitutes an alternative to their recording at different points of the grain storage bins (Iguaz et al., 2004). Therefore, the objectives of the present study are:

1) To test a mathematical model used to predict moisture content within wheat stored in a metallic silo;
2) To verify the tested model by comparing the experimental results of moisture content of wheat grain stored in a metallic silo with the predicted ones.

MATERIALS AND METHODS

The tested model

To test the diffusive moisture transfer model developed by Ismail et al. (2008), the following assumptions were made:

1) The air within the bulk (Interstitial air) and the grain were in thermal and sorption equilibrium at every location within the silo;
2) Radiation heat transfer was negligible;
3) The thermo-physical properties of grain, air and silo remained constant throughout the experiment and the grain was a homogeneous medium;
4) Internal heat generation within the grain bulk was negligible;
5) Initial moisture content and temperature of the grain were uniform throughout the silo;
6) Moisture and heat transfer were due to diffusion and conduction processes, respectively in the radial (r) and the axial (z) coordinates (it is assumed to possess circular symmetry about a vertical axis). Convective heat and moisture transfer were negligible;
7) Moisture and temperature distribution were symmetrical about the central vertical axis of the silo;
8) Silo wall temperatures were equal to ambient air ones;
9) The metallic silo was completely sealed and it was entirely filled with wheat grain.

As stated in assumption number 6 and reported by Ismail et al. (2008), the partial differential equation of unsteady state water vapour diffusion in polar coordinates for simulating wheat grain moisture distribution inside the silo is of the following form:

$$\frac{\partial PV}{\partial t} = D\left[\frac{1}{r}\frac{\partial PV}{\partial t} + \frac{\partial^2 .PV}{\partial r^2} + \frac{\partial^2 PV}{\partial z^2}\right] \quad (1)$$

Where:

$\frac{\partial PV}{\partial t}$ = Rate of change of water vapour pressure (Pa/s);
D = Water vapour diffusion coefficient through air (m^2/s);
r = Radial distance from the silo centre to the spatial element node in question (m);

$\frac{\partial PV}{\partial r}$ = Water vapour pressure gradient in the radial coordinate (Pa/m);
$\frac{\partial PV}{\partial z}$ = Water vapour pressure gradient in the axial coordinate (Pa/m).

To simulate the moisture content distribution inside the silo, the finite difference method was used to solve numerically the partial differential Equation 1. The silo was divided into ninety one spatial elements, seven radially and thirteen axially as shown in Figure 1. The length of the increments in the radial and axial coordinates is 5 cm except for exterior ones for both coordinates and central ones in the radial coordinate, which is 2.5 cm. This is because greater accuracy is obtained when using a narrow space interval (Leinhard, 2006). The nodes numeration (pivots) of the spatial elements in the silo is as follows:

- Radial coordinate (r): 0, 1, 2, …, 6;
- Axial coordinate (z): 0, 1, 2, …, 12.

Figure 2 depicts the 91 spatial elements numeration grid on a cross-section through the central vertical axis of the silo. Chung's sorption equation with the following form as reported in Aviara et al. (2006) was used in the tested diffusive moisture transfer model:

$$RH = \exp\left[\frac{-A}{(T+C)}\exp(-B.M)\right] \quad (2)$$

Where:

RH = Relative humidity of the interstitial air, decimal A, C and B = grain-dependent constants;
T = grain temperature (°C);
M = grain moisture content, decimal (d.b.).

It is well known that when a temperature gradient exists in a grain bulk with uniform moisture content, pressure and concentration gradients of water vapour pressure exist parallel to the temperature gradient causing water vapour to diffuse from the high temperature region to the low temperature region. This fact could be mathematically interpreted in simulating the moisture contents of the stored wheat by assuming that moisture of grain will be unchanged for a certain period of time while there is a temperature gradient being established within the grain bulk. Consequently, this will lead to the establishment of:

1) A relative humidity (RH) gradient parallel to the temperature gradient as seen from Equation 2.

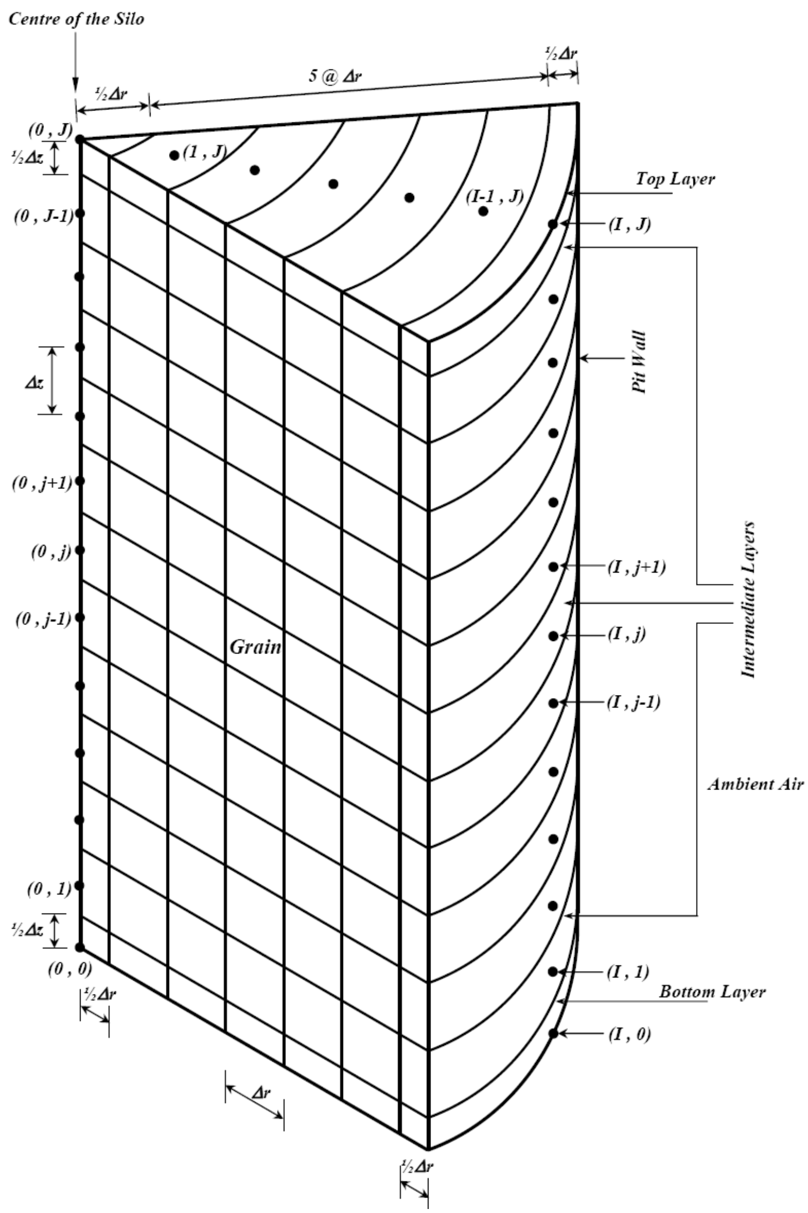

Figure 1: Schematic diagram of the silo sector divided into (I + 1) radial and (J+1) vertical spatial elements.

2) A saturated water vapour pressure (PV_s) gradient parallel to the temperature gradient because saturated water vapour is a function of the interstitial air temperature as shown in Equation 3 given as:

$$PV_s = RR.\exp\left[\frac{AA + BB.T + CC.T^2 + DD.T^3 + EE.T^4}{FF.T - GG.T^2}\right] \quad (3)$$

$(273.16 \leq T \leq 533.16)$

Where: T = temperature, k; *RR, AA, BB, CC, DD, EE, FF and GG* = Constants.

3) A water vapour pressure (PV) gradient parallel to the temperature gradient because $PV = RH * PV_s$.

The numerical solution of the partial differential Equation 1 was carried out by replacing each derivative of the partial differential equation at the node of the spatial element in question by a finite difference approximation in terms of the values of water vapour pressure at the node itself and the neighbouring nodal points. A central difference scheme in the space domain and a forward one in the time domain were used. The criterion of stable solution with finite difference equations is satisfied when the finite difference time increment (Δt) and the finite difference space

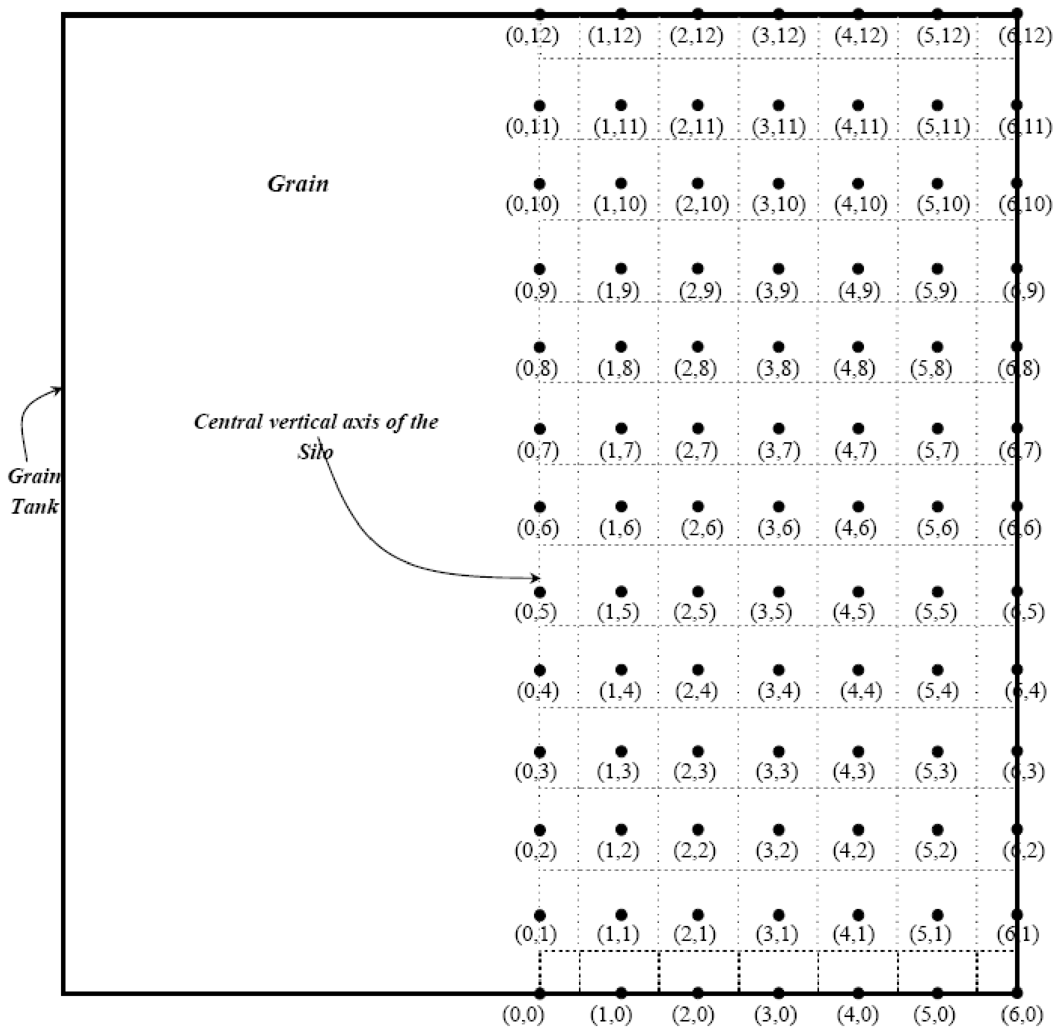

Figure 2: Spatial elements numeration grid of the spatial elements on a cross-section through the central vertical axis of the silo.

increments (Δr and Δz) are chosen correctly. The correct choice of these increments means that the coefficients of the obtained difference equations are greater than zero and also the coefficient of the term $PV_{i,,j:p}$ ($0 \le i \le I$ and $0 \le j \le J$) should be greater or equal to zero, that is, not negative. When this coefficient is negative, the solution of the finite difference equation becomes negative. The water vapour pressure of each spatial element is denoted by three subscripts, the first two were separated from the third by a colon, for example, $PV_{i,j:p}$ means the water vapour pressure of spatial element i, j at time t and $PV_{i,j:p+1}$ means the water vapour pressure of the same spatial element at time $t + \Delta t$. Then, the moisture content simulation equations of the spatial elements of the silo (Figure 1) were derived as follows:

Exterior spatial element of the bottom layer (I, 0)

Equation 1 was converted to a difference form as follows:

$$\frac{\partial PV}{\partial t} = D\left(\frac{1}{r}\frac{\partial PV}{\partial t} + \frac{\partial^2 .PV}{\partial r^2} + \frac{\partial^2 PV}{\partial z^2}\right)$$

$$\left(\frac{\partial PV}{\partial t}\right)_{I,0:P} = \frac{PV_{I,0:p+1} - PV_{I,0:p}}{\Delta t}$$

$$\left(\frac{1}{r}\frac{\partial PV}{\partial r}\right)_{I,0:p} = 0 \text{ because } \frac{\partial PV}{\partial r} = 0 \text{ at } r = I$$

$$\left(\frac{\partial^2 PV}{\partial r^2}\right)_{I,0:p} = \frac{PV_{I+1,0:p} + PV_{I-1,0:P} - 2PV_{I,0:p}}{\Delta r^2}$$

To eliminate the fictitious element I+1.0 the following boundary condition equation was used:

$$\left(\frac{\partial PV}{\partial r}\right)_{I,0:p} = \frac{PV_{I+1,0:p} - PV_{I-1,0:p}}{2\Delta r} = 0 \quad \text{or}$$

$$PV_{I+1,0:p} = PV_{I-1,0:p}$$

Then this gives: $\left(\frac{\partial^2 PV}{\partial r^2}\right)_{I.0:p} = 2\left(\frac{PV_{I-1,0:p} - PV_{I,0:p}}{\Delta r^2}\right)$

The fictitious element I-1,0 was eliminated by the following boundary condition given as:

$$\left(\frac{\partial PV}{\partial z}\right)_{I,0:p} = \frac{PV_{I,1:p} - PV_{I,-1:P}}{2\Delta z} = 0 \quad \text{or}$$

$$PV_{I,1:p} = PV_{I,-1:P}$$

Then this leads to: $\left(\frac{\partial^2 PV}{\partial z^2}\right)_{I.0:p} = 2\left(\frac{PV_{I,1:p} - PV_{I,0:p}}{\Delta z^2}\right)$

Equation 1 may be written in a difference for this element as:

$$\frac{PV_{I,0:p+1} - PV_{I,0:p}}{\Delta t} = D\left[\frac{2}{\Delta r^2}\left(PV_{I-1,0:p} - PV_{I,0:p}\right) + \frac{2}{\Delta z^2}\left(PV_{I,1:p} + PV_{I,0:p}\right)\right]$$

$$PV_{I,0:p+1} = \left(\frac{2D\Delta t}{\Delta r^2}\right)PV_{I-1,0:p} + \left(\frac{2D\Delta t}{\Delta z^2}\right)PV_{I,1:p} + \left(1 - \frac{2D\Delta t}{\Delta r^2} - \frac{2D\Delta t}{\Delta z^2}\right)PV_{I,0:p} \quad (4)$$

The stability criterion for Equation 4 is given as:

$$\left(\frac{D\Delta t}{\Delta r^2} + \frac{D\Delta t}{\Delta z^2}\right) \leq \frac{1}{2}$$

Interior spatial elements of the bottom layer (i, 0) 1≤ *i*≤*I*-1

$$\frac{\partial PV}{\partial t} = D\left(\frac{1}{r}\frac{\partial PV}{\partial t} + \frac{\partial^2 .PV}{\partial r^2} + \frac{\partial^2 PV}{\partial z^2}\right)$$

$$\left(\frac{\partial PV}{\partial t}\right)_{i,0:P} = \frac{PV_{i,0:p+1} - PV_{i,0:p}}{\Delta t}$$

$$\left(\frac{1}{r}\frac{\partial PV}{\partial r}\right)_{i,0:p} = \frac{1}{r}\left(\frac{PV_{i+1,0:p} - PV_{i-1,0:p}}{2\Delta r}\right)$$

$$\left(\frac{\partial^2 PV}{\partial r^2}\right)_{i,0:p} = \frac{PV_{i+1,0:p} + PV_{i-1,0:p} - 2PV_{i,0:p}}{\Delta r^2}$$

$$\left(\frac{\partial^2 PV}{\partial z^2}\right)_{i,0:p} = \frac{PV_{i,1:p} + PV_{i-1:p} - 2PV_{i,0:p}}{\Delta z^2} = \frac{2PV_{i,1:p} - 2PV_{i,0:p}}{\Delta z^2}$$

Equation 1 in a difference form for these elements is:

$$PV_{i,0:p+1} = \left(\frac{D\Delta t}{2r\Delta r} + \frac{D\Delta t}{\Delta r^2}\right)PV_{i+1,0:p} + \left(\frac{D\Delta t}{\Delta r^2} - \frac{D\Delta t}{2r\Delta r}\right)PV_{i-1,0:p} + \left(\frac{2D\Delta t}{\Delta z^2}\right)PV_{i,1:p} + \left(1 - \frac{2D\Delta t}{\Delta r^2} - \frac{2D\Delta t}{\Delta r^2}\right)PV_{i,0:p}$$

The stability criterion for Equation 5 is given as:

$$\left(\frac{D\Delta t}{\Delta r^2} + \frac{D\Delta t}{\Delta z^2}\right) \leq \frac{1}{2}$$

Center spatial element of the bottom layer (0.0)

Due to the mass distribution symmetry about the vertical axis of the silo, moisture will be transferred only through the outer face of this spatial element. Since $\frac{\partial PV}{\partial r} = 0$ at r = 0, therefore $\frac{1}{r}\frac{\partial PV}{\partial r} = 0$ assumes the indeterminate form $\frac{0}{0}$ at this node. To overcome this problem Maclaurin's series was used.

PV'(r) = PV'(0) + rPV''(0) + ½ r²PV''' (0) + ..., but PV'(0) = 0, so the limiting value of $\frac{1}{r}\left(\frac{\partial PV}{\partial r}\right)$ as r tends to zero is the value of $\frac{1}{r}\frac{\partial PV}{\partial r}$ at r = 0, hence, the differential form of Equation 1 may be written as:

$$\frac{\partial PV}{\partial t} = D\left[2\frac{\partial^2 PV}{\partial r^2} + \frac{\partial^2 PV}{\partial z^2}\right]$$

The aforementioned equation in a finite difference is given as:

$$\left(\frac{\partial PV}{\partial t}\right)_{0,0:p} = \frac{PV_{0,0:p*1} - PV_{0,0:p}}{\Delta t}$$

$$\left(2\frac{\partial^2 PV}{\partial r^2}\right)_{0,0:p} = 2\left(\frac{PV_{1,0:p} + PV_{-1,0:p} - 2PV_{0,0:p}}{\Delta r^2}\right) = 2\left(\frac{2PV_{1,0:p} - 2PV_{0,0:p}}{\Delta r^2}\right)$$

$$\left(\frac{\partial^2 PV}{\partial z^2}\right)_{0,0:p} = \frac{PV_{0,1:p} + PV_{0,1:p} - 2PV_{0,0:p}}{\Delta z^2} = \frac{2PV_{0,1:p} - PV_{0,0:p}}{\Delta z^2}$$

Equation 1 in a difference form for this element is:

$$PV_{0,0:p+1} = \left(\frac{4D\Delta t}{\Delta r^2}\right)PV_{1,0:p} + \left(\frac{2D\Delta t}{\Delta z^2}\right)PV_{1,0:p} + \left(1 - \frac{4D\Delta t}{\Delta r^2} - \frac{2D\Delta t}{\Delta r^2}\right)PV_{0,0:p}$$

(6)

The stability criterion for Equation 6 is given as:

$$\left(\frac{2D\Delta t}{\Delta r^2} + \frac{D\Delta t}{\Delta z^2}\right) \leq \frac{1}{2}$$

The remaining six finite difference equations needed for moisture simulation were obtained following the same procedure adopted in Equations 4 to 6 as shown in the report of Ismail et al. (2008). At the end of each finite time increment, the water vapour pressure in the interstitial air of each spatial element was calculated using the water vapour pressures computed for the previous time increment. Thereafter, the calculated simulated water vapour pressures were converted into corresponding moisture contents by carrying the following computations:

- By knowing the spatial element temperature, the saturated water vapour pressure in the interstitial air of the element was calculated;
- Dividing the simulated water vapour pressure by the saturated water vapour pressure calculated in step 1, the relative humidity of the interstitial air within the element was obtained;
- The moisture content for each spatial element was calculated using the Chung's sorption equation in the following form as reported in the report of Aviara et al. (2006):

$$M = E - F.\ln\left[-(T + C).\ln(RH)\right]$$

(7)

Where:

E, F, C = grain dependent constants;
T = grain temperature (°C);
M = Grain moisture content, decimal;
RH = Relative humidity of interstitial air decimal.

The diffusive moisture transfer and the conductive transfer models were written into one computer programme using VISUAL FORTRAN 6.5 programming language and run on a PC. Input data for the programme are initial grain temperature, initial grain moisture content, ambient air temperature, storage time, number of spatial elements in both directions, finite difference spatial increment in both directions and thermo-physical properties of grain and silo wall material. The programme calculated the grain temperature and the grain moisture content at the end of each finite time increment for every spatial element using the temperatures and the partial water vapour pressures calculated for the previous time increment, that is, stationary iterative method.

Experimental study

Experiments of the present study were conducted at The Agricultural and Veterinary Research Station of King Faisal University, Kingdom of Saudi Arabia. The following materials, equipment and methods were used in carrying out the experimental work of the study.

Wheat grain: 200 kg of wheat were purchased from Al-Ahsa local market and kept in airtight plastic containers so as to be used as the stored product in the silo.

Experimental storage silo: It is a typical cylindrical metallic silo and was constructed from galvanized zinc sheets (3 mm thickness) with dimensions of 60 cm for each diameter and height.

Reethorpe-type moisture sensors: They were marketed by R.D.S (Agricultural) Ltd., Stored, Glos., England as described by Gough (1980). The sensor consists of two electrodes – a perforated metal tube 18 mm outside diameter, 60 mm long and threaded metal rod 4.5 and 100 mm long, respectively fitted coaxially in the tube as shown in Figure 3. Before starting the recording of wheat moisture contents, these sensors were calibrated using the standard oven method. The sensors were connected to a Marconi moisture meter through a 12-way switch box.

Marconi moisture meter: It was of type TF933D. The principle employed in the instrument is the variation of electrical conductivity of the specimen with its moisture content.

Ordinary mercury in glass thermometer: It was used to

Figure 3: Reethorpes (moisture sensors).

measure the initial grain temperature before commencing the wheat storage.

Copper constantan thermocouples: They were used to record grain temperatures in specific locations inside the silo.

Data logger: It was of data logger made commercially marketed by Data-T Devices, Burwell, Cambridge, UK. The output of the thermocouples readings is given in °C with an accuracy of ±0.2°C. The recorded data in the logger was retrieved later by Microsoft® Excel spreadsheet software.

Sticking tape and twist ties: Thermocouples were fixed to their specified positions using a sticking tape, while moisture sensors were fixed by using the sticking tape or the twist ties.

Silicon glue: It was used for closing the grain silo filling hole through which thermocouples and moisture sensors cables were inserted.

About 130 kg of wheat were taken from the airtight plastic containers and loaded inside the silo. The silo was raised few centimetres above the soil by putting one layer of building brick underneath the silo. Both initial grain temperature and grain moisture content were measured and found to be 36.5°C and 9.58% (w.b.), respectively. 21 thermocouples and 9 moisture sensors were used to record grain temperatures and grain moisture contents, respectively inside the silo. One other thermocouple was used to record the ambient air temperature. The thermocouples were fixed at their specified positions by fixing them to seven glass-tubes, three thermocouples per tube. The data logger was configured to record grain temperatures at 24 h intervals during the storage period. The temperatures of wheat were recorded at the silo centre and at two locations equidistant around two concentric circles (30 cm and 60 cm diameter) at each of three depths (0, 30 and 60 cm), respectively.

As stated earlier in assumption 6, the model assumes no heat transfer in the circumferential coordinate. Therefore, the three temperature readings of each concentric circle were averaged for each depth and radius combination. This means that wheat temperatures at nine locations inside the silo and ambient air temperatures were recoded for each time interval of 24 h. Wheat moisture contents were recorded at the same nine locations but only one moisture sensor was used per concentric circle. The moisture sensors were placed at the three depths with sensor axis always horizontal and were arranged in spiral manner so that they did not interfere with each other. The sensors were fixed at their specified positions using a sticking tape to fix them to the inner silo surface or a twist tie to tie them to the nearest glass tube. The sensors were connected to the Marconi moisture meter through a 12-way switch box. Wheat moisture content readings were taken at 13:30 PM weekly. Placing of the thermocouples and the moisture sensors was carried out before and during the pouring of wheat inside the silo.

Silicon glue was used to close the spaces in the silo filling hole through which the thermocouples and the moisture

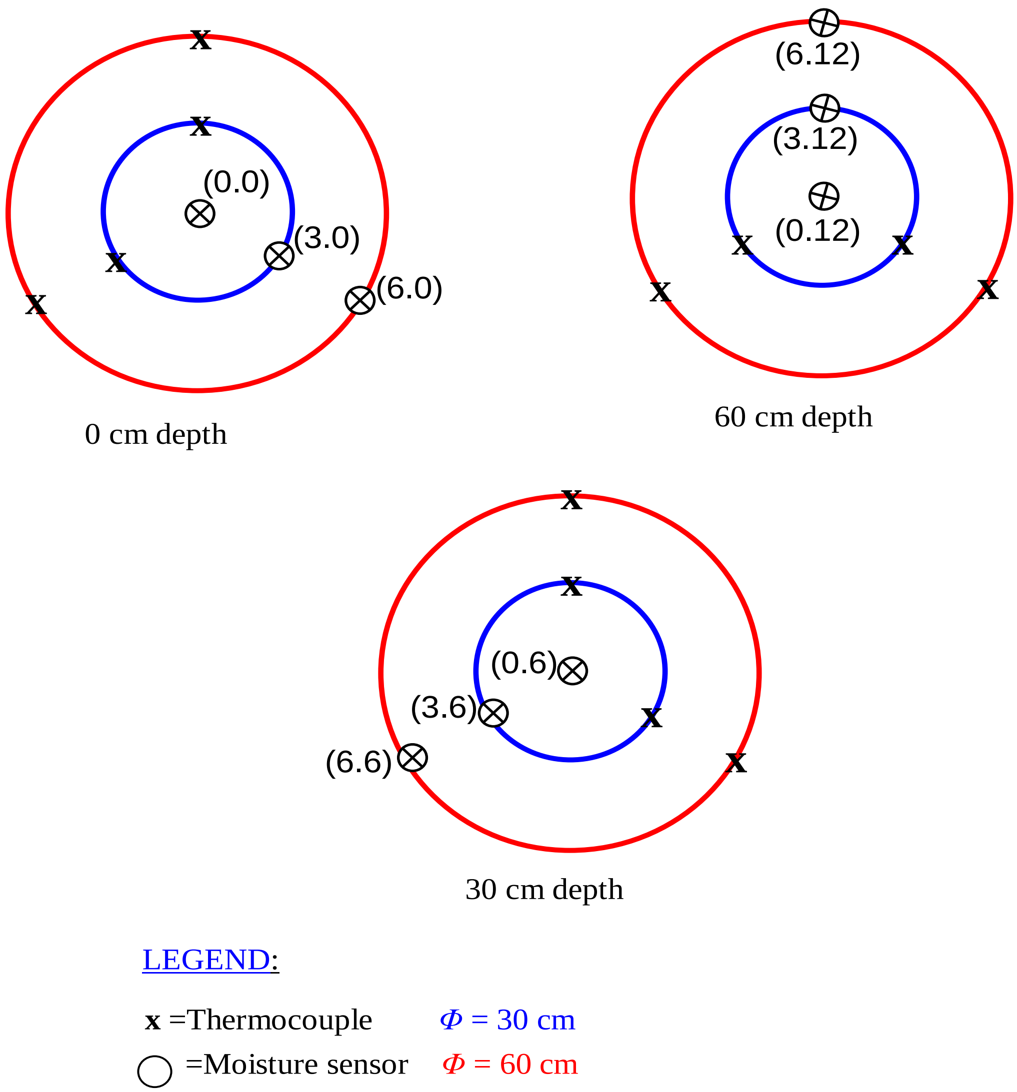

Figure 4: Plan view of the concentric circles along the grain silo height showing thermocouples and moisture sensors configuration.

sensors were inserted in order to ensure that the silo is an air-tight container. Figure 3 shows the configuration of the thermocouples and the moisture sensors inside the silo. The wheat grain was stored for a period of 13 weeks, that is, 91 days.

RESULTS AND DISCUSSION

Graphical presentation of the tested diffusion moisture transfer model

Referring to Figure 2, Figures 5 to 12 show measured and predicted grain moisture contents in addition to measured temperatures for eight spatial elements out of nine. This is because the measured grain moisture contents data of the spatial element (3,0) showed abnormal readings throughout the experimental course and accordingly it was excluded. These figures show a state of unattainable moisture equilibrium under the storage conditions of the silo. This could be due to the fact that the moisture content of wheat in any part of the silo is a function of the equilibrium relative humidity in the interstitial air in that location, which in turn is dependent on the interstitial air temperature in the same location.

It is clear from the graphs that the major change of moisture takes place during the first two weeks of storage period in general. This confirms that diffusion of moisture within stored wheat is a slow process. These results are in line with the report of Thorpe (1981, 1982), Mohamed (2007) and Ismail et al. (2008). Despite the fact of measured grain temperature variation in the radial direction in particular, no accumulation of moisture was detected in the silo as clearly shown by the graphs. This

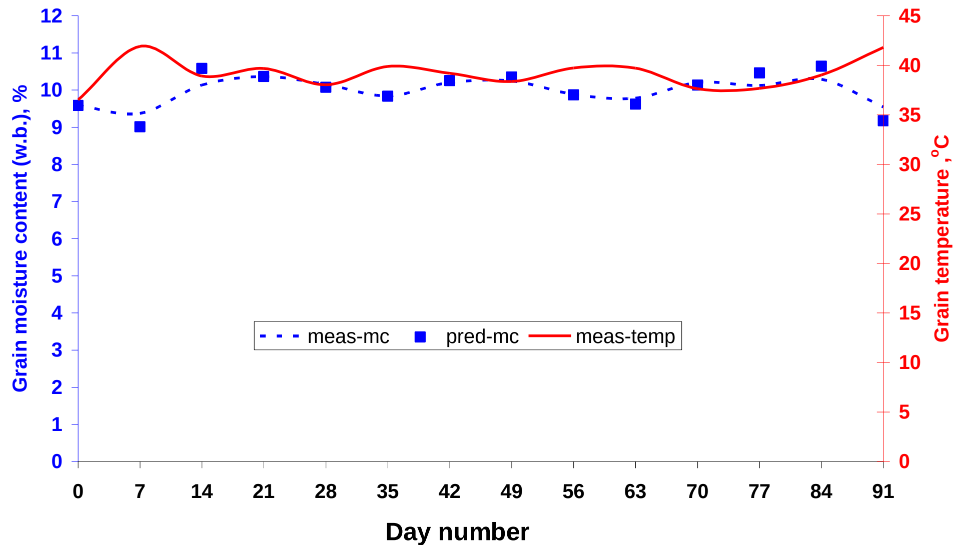

Figure 5: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (0.0).

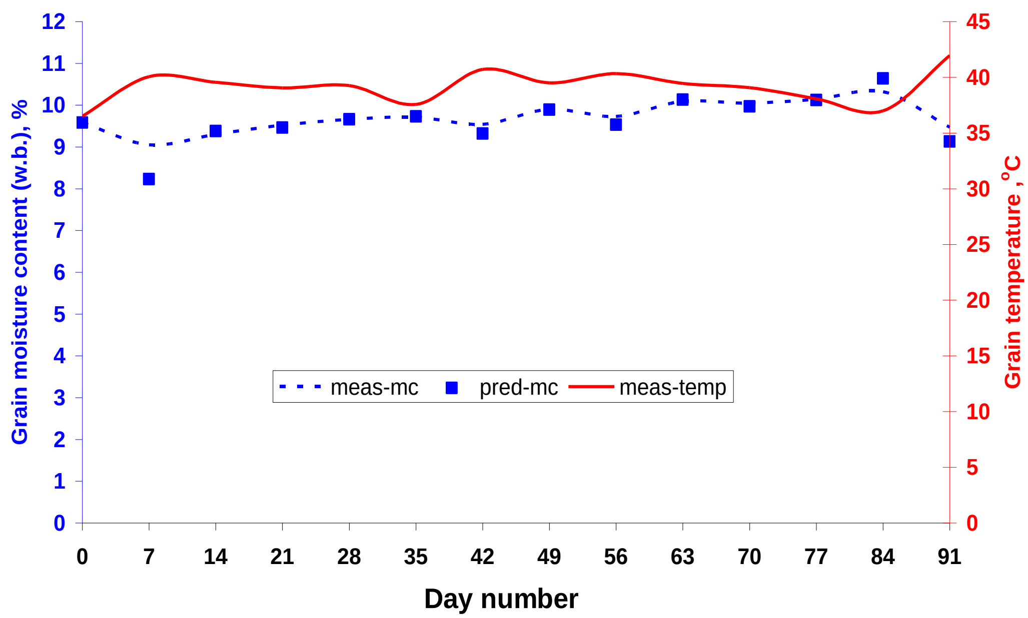

Figure 6: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (6.0).

means that the granular nature of the bulk stored wheat, which is considered as a low porous granular grain compared to other crops enhances moisture movement to take place by diffusion parallel to vapour pressure gradient. It also restricts the convective moisture transfer to be of no or minimal effect.

This fact supports the validity of the raised assumption that moisture transfer within wheat stored in the silo is only due to water vapour pressure diffusion, and hence, convective moisture transfer is neglected. Generally, it is clear that graphical presentation as seen in these figures shows a very close agreement between measured and predicted moisture contents of the stored wheat for all spatial elements within the silo.

Statistical validation of the tested diffusion moisture transfer model

The parameters used in the statistical validation of the

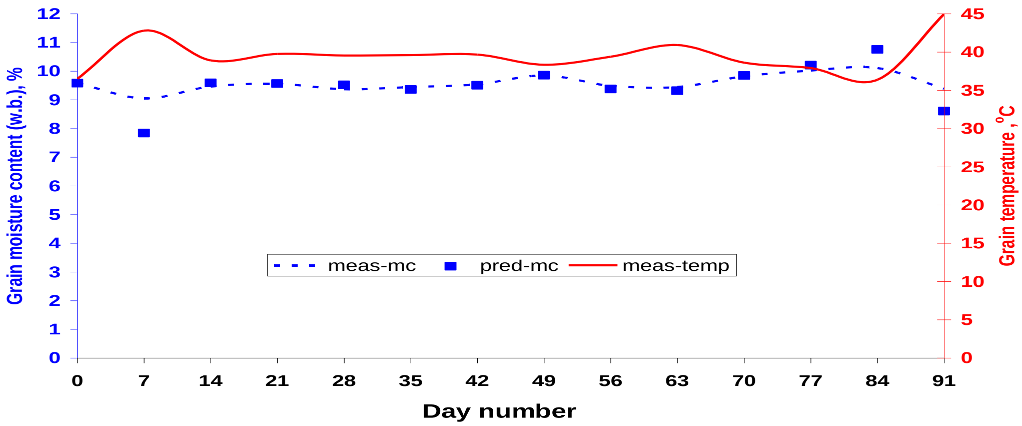

Figure 7: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (0.6).

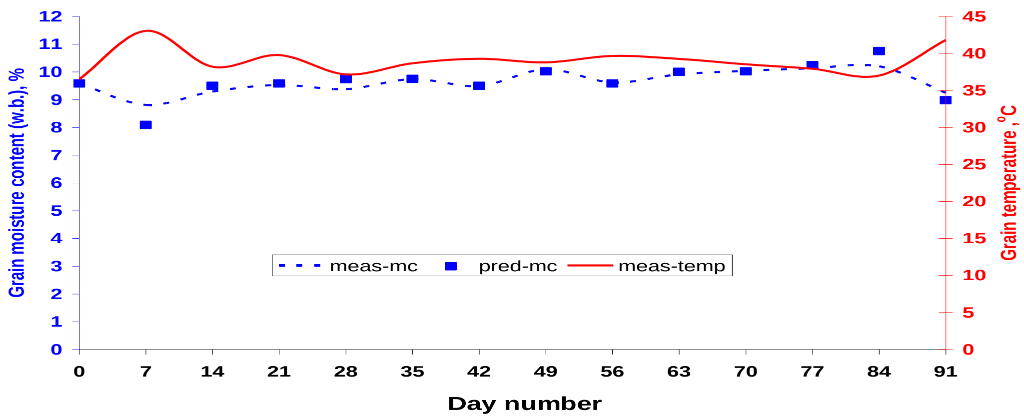

Figure 8: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (3.6).

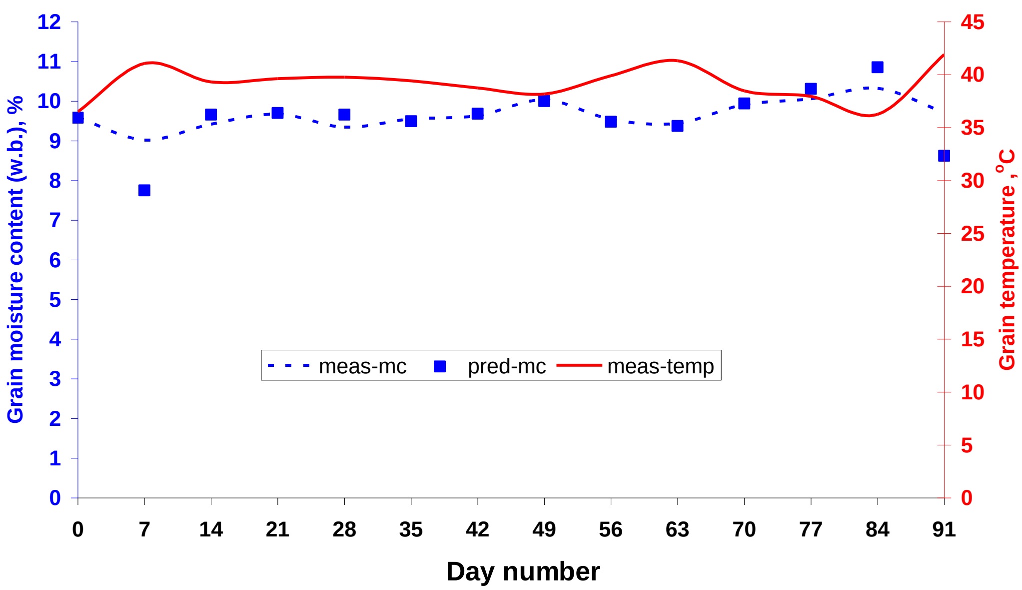

Figure 9: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (6.6).

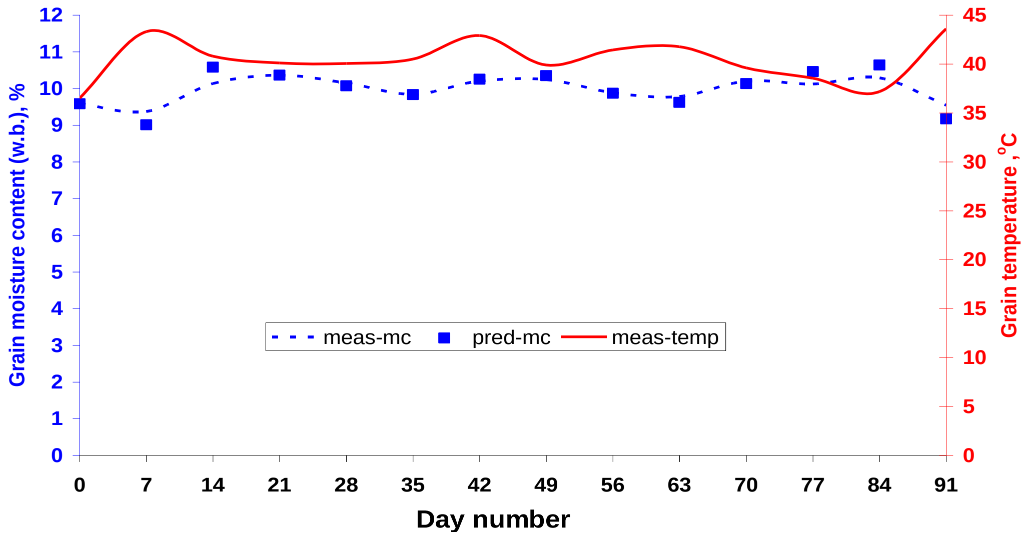

Figure 10: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (0.12).

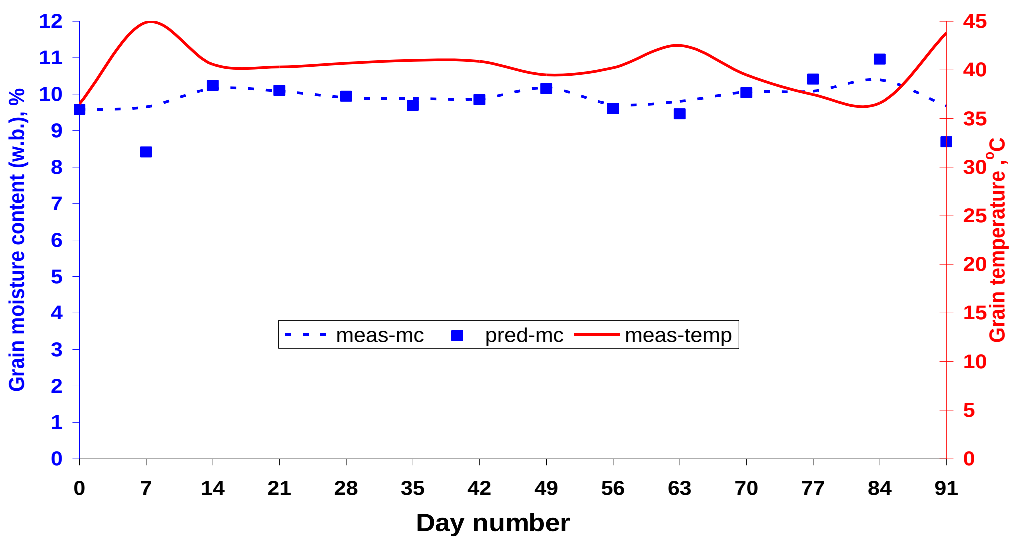

Figure 11: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (3.12).

tested model include the followings:

Average model error (AME) =

$$\frac{\sum_{i=1}^{n}\left(measured_i - predicted_i\right)}{n} \quad (8)$$

Average absolute difference (AAD) =

$$\frac{\sum_{i=1}^{n} abs\left(measured_i - predicted_i\right)}{n} \quad (9)$$

Standard error estimate (SEE) =

$$\sqrt{\frac{\sum_{i=1}^{n}\left(measured_i - predicted_i\right)^2}{n}} \quad (10)$$

Where:

$measured_i$ = measured grain moisture content, percent (w.b.);

$predicted_i$ = predicted grain moisture content, percent (w.b.);

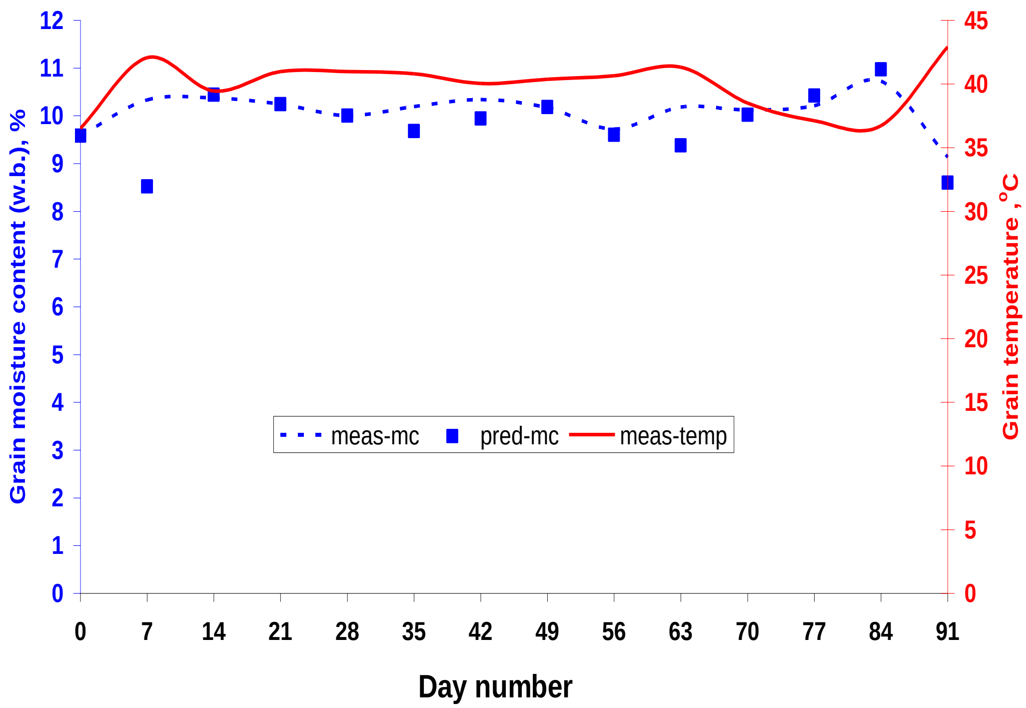

Figure 12: Measured and predicted grain moisture contents in addition to measured temperatures at the spatial element (6.12).

Table 1: Average model error (AME), average absolute difference (AAD) and standard error of estimate (SEE) between the measured and the predicted moisture content (%, w.b.) at eight locations inside the silo (Figure 3).

Spatial element	AME (%, w.b.)	AAD (%, w.b.)	SEE (%, w.b.)
(0,0)	– 0.02	0.23	0.30
(6,0)	0.19	0.39	0.50
(0,6)	0.10	0.18	0.29
(3,6)	– 0.01	0.23	0.32
(6,6)	0.12	0.33	0.50
(0,12)	0.10	0.28	0.44
(3,12)	0.13	0.35	0.51
(6,12)	0.29	0.37	0.59

n = number of observations.

The aforementioned parameters were calculated using Microsoft® Office Excel spreadsheet software. It is stated by Abbouda (1984) that an accurate model should have an AME and AAD close to zero and small SEE. Table 1 presents the magnitude of these parameters obtained in the present study. From Table 1 AME, AAD and SEE range from - 0.02 to 0.27, 0.16 to 0.35 and 0.23 to 0.59% (w.b.), respectively. This indicates that the model predicted grain moisture contents adequately and within the bounds of the experimental error. The two sample independent t-test was carried out using Microcal Origin 7 software package.

As shown in Table 2 the t-test ($P<0.05$) was done to see if there is a significant difference between the sample means of measured and predicted moisture contents at the eight locations in the silo. Since the three indicators of the null hypothesis (H_o: $\mu_1 = \mu_2$) show there is a zero value falling within the 95% CI for $\mu_1 = \mu_2$, $|t_o| \leq t_1$ and $P>0.05$ at these locations inside the silo. This implies that there is no evidence to reject the null hypothesis. This means that on the basis of the present data there is no significant difference between the two methods of moisture content determination at these eight locations. Again this confirms that the tested model is so accurate in predicting the moisture content of grains with size similar to that of

Table 2: Two samples independent t-test ($P < 0.05$) to see if there is a significant difference between the sample means of measured and predicted moisture content (%, w.b.) at eight locations inside the silo (Figure 2).

Spatial element	95% CI for $\mu_1 = \mu_2$	$\mu_1 = \mu_2$ vs $\mu_1 \neq \mu_2$			
		t_0	t_1	P	df
(0,0)	(– 0.34, 0.31)	– 0.11	2.06	0.91	26
(6,0)	(– 0.21, 0.58)	0.95	2.06	0.35	26
(0,6)	(– 0.27, 0.46)	0.52	2.06	0.61	26
(3,6)	(– 0.42, 0.38)	0.1	2.06	0.92	26
(6,6)	(– 0.25, 0.52)	073	2.06	0.47	26
(0,12)	(– 0.32, 0.49)	0.43	2.06	0.67	26
(3,12)	(– 0.35, 0.52)	0.4	2.06	0.70	26
(6,12)	(– 0.16, 0.70)	1.29	2.06	0.21	26

CI = Confidence interval, decimal; μ_1 = Population mean of the experimental moisture content (w.b.), percent; μ_2 = Population mean of the predicted moisture content (w.b.), percent; t_0 = Calculated value of test statistic; t_1 = t-distribution critical value (tabulated value) at the desired critical alpha level of 0.05 and the corresponding degrees of freedom; df = Degrees of freedom; P = Probability of being wrong if the null hypothesis (H_o) is rejected at the desired critical alpha level of 0.05, decimal.

wheat.

Conclusions

The following conclusions were drawn from this study:

- Under the storage conditions of the experimental silo, measured and predicted moisture contents show unattainable moisture content equilibrium. This is because moisture content is dependent upon the equilibrium relative humidity in the interstitial air within stored wheat bulk, which varies only according to water vapour pressure gradient. This established water vapour pressure gradient is considered to be the driving force for moisture diffusion inside the stored wheat bulk. In addition, the properties of the porous granular bed of wheat enhanced moisture diffusion rather than moisture convection;
2) The tested diffusion moisture transfer model confirms that the major change of moisture content within wheat grains stored in silo took place during the first two weeks of storage in general. This supports the fact that, diffusion of moisture within the stored wheat is a slow process;
3) The tested diffusion moisture transfer model predicts wheat moisture contents very accurately and within the bounds of the experimental error. The SEE between the measured and the predicted moisture contents is 0.29 to 0.59% (w.b.). This result reveals that Chung's sorption equation is adequately successful in simulating moisture content within bulk wheat stored in the silo.
4) Computer simulation is reliable, inexpensive and a fast technique method could be an alternative for predicting moisture contents and temperatures of grains with size similar to that of wheat.

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