Application of a Mass Transfer Model for Simulation and Prediction of Moisture Distribution in Stored Corn Grains

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Abstract:

The two-dimensional finite difference model, developed by Abbouda, *et al*. (1992b), was applied to predict the moisture changes of corn grains stored in vertical standing, cylindrical steel bins. The water generated by respiration of corn was incorporated into the model. A comparison between the predicted and the measured moisture data made validation of the model. In general, they were in good agreement for a test period of one year. Results indicated that the model and the parameter values used in the model are applicable for predicting moisture of unventilated stored grain.

The grain lost moisture during storage. The average moisture content at the end of a one-year period dropped from 10.00% to 9.25% and from 12.00% to 9.84% for the small bins. For the large bins, moisture content dropped from 12.00% to 10.31% and from 10.00% to 9.60%. Bin size and initial moisture content caused significant effects on the moisture changes and corn grains quality under the unventilated environmental conditions of Al-Ahsa, Saudi Arabia.

Introduction

Cereal grains and their products are hygroscopic in nature, i.e., they will sorbs moisture from or give it up to the surrounding atmosphere until they are in equilibrium with it. Each grain displays a characteristic water vapor pressure at a given moisture content and temperature. If the vapor pressure of the moisture in the grain is above that in the ambient air, the grain will lose moisture to the air until its vapor pressure approaches that of the air (Chung and Pfost, 1967). But above all, moisture content is regarded as the single most important quality related property of grain. Grain can be stored at low moisture for long periods without spoilage because of the lower rates of growth and development of microorganisms, insects, and mites as well as lower rate of chemical and physical activities (Hunt and Pixon, 1974). Seasonal variations in ambient temperatures can cause safe moisture contents of stored grains to unsafe level due to migration or redistribution of moisture within the storage. Under certain conditions, localized increase in moisture content results in an environment conducive to growth of storage fungi as well as accelerated growth of insects, which sometimes produce toxins that make the grain hazardous for human consumption. The qualitative and quantitative nature of moisture migration can vary with the kind and quality of stored grain, size and shape of storage facilities, initial temperature and moisture content of the grain, and the local climatic conditions. Therefore, the proper design and management of storage require understanding and prediction of moisture distribution under different grain and climatic conditions (Khankari, *et al*. 1994 and 1995a).

Moisture will transfer by convective air currents in a grain mass with uniform moisture content, if temperature gradient exists in the mass. Holman and Carter (1952), in their study of farm-type steel bins, found that the degree of moisture migration depended on initial moisture content (IMC) and was slower in small bins than large bins. Schmidt (1955) reported considerable moisture migration that generally depending on harvesting time. Hellevang and Hirning (1988) conducted a field study on 16 storage bins of various sizes during April through August. They observed an average decrease of 2.56% moisture content at the top surface with an average increase of 0.45% moisture content at depths of 0.6 - 1.8 m below the top surface.

Experimental studies of moisture distribution are labor cost, and time intensive, and can yield only specific information related to the local experimental conditions. In addition to this, lack of reliable and inexpensive humidity sensors make the field studies of moisture distribution very difficult. In such a situation, well-validated computational models can make qualitative and quantitative estimates of moisture and temperature distribution in stored grains, which in turn, can help in improving the understanding of moisture migration behavior under different grains and climatic conditions (Khankari, *et al*. 1995b).

Many researchers have studied the movement of heat and moisture in stored grains. But most work has been dealing with drying or aeration problems where forced ventilation exists (Hunt and Pixon, 1974). Lo, *et al.* (1975) simulated moisture changes in wheat storage under the influence of weather temperature variation. They found that the range of seasonal changes in grain moisture content decreased as the distance from wall increased. Tanka and Yoshida (1984) developed a simulation model for heat and moisture transport mechanisms in a grain storage silo. They used the mass fraction of water vapor as a dependent variable. Nguyen (1986) developed a two-dimensional, transient model to describe moisture migration in stored grains due to the natural convection. He showed that natural convection currents are strong during daytime and weak during nighttime when conduction is a dominant mode of heat transfer. Casada and Young (1989) developed a finite difference model to predict the heat and moisture transport in shelled peanuts. The rate of grain moisture change was simulated through a thin layer drying equation, which assumed convective mass transfer from the grain surface. They reported that such an approach caused difficulty with maintaining a proper moisture balance between the air and peanuts. Smith and Sokhansanj (1990) developed a natural convection heat transfer model in which the density of air was assumed to be a function of temperature and absolute humidity. Their calculations of the moisture contents were based on the drying rate equation with constant relative humidity without involving transport phenomena and basic principle of moisture conservation. Khankari, *et al*. (1994 and 1995a) developed two numerical models to simulate the moisture migration process by using the sorption isotherm concept in the transport equations. Abbouda, *et al.* (1992b) developed a two-dimensional, finite difference model to simulate milo moisture distribution in a cylindrical steel bins under unventilated storage conditions. Their model showed good agreement with experimental results.

The objectives of this study were: (1) to test the applicability of the mass transfer model developed by Abbouda, *et al*. (1992b) under the weather conditions of the Eastern Province of Saudi Arabia and (2) to observe the moisture changes of corn grains stored in cylindrical steel bins as the ambient air temperature, initial moisture content, and bin size varied.

Mathematical Model

The mathematical model previously developed by Abbouda, *et al.* (1992b) was applied and validated in this study under Saudi Arabia conditions. The model is based on the following partial differential equation of mass transfer in two-dimensional cylindrical coordinate:

$$\frac{\partial w}{\partial t} = D_g \left[\frac{\partial^2 w}{\partial^2 r} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial^2 z}\right] \tag{1}$$

The boundary conditions were assumed to be:

$$\left|\frac{\partial w}{\partial r}\right|_{r=0} = 0 \tag{2}$$

$$w\big|_{z=0} = WE \tag{3}$$

$$w\big|_{r=R} = WE \tag{4}$$

$$w\big|_{z=H} = WE \tag{5}$$

In a heat transfer model, a sector of cylindrical steel bin was divided into a finite number of spatial elements in the axial and radial directions (Abbouda, *et al.* 1992a). Heat balance equation was applied to each element to derive the equations for predicting grain temperatures. In the mass transfer model, similar approach was taken to convert partial differential equation 1 into a finite difference form for predicting moisture.

Assuming that the mass transfer coefficient is a constant, the predicted moisture content of an interior element (m, n) at the end of time interval $(t + \Delta t)$ is expressed as (see nomenclature for symbol definitions):

$$W'_{m,n} = \left[\frac{2n+1}{2nU}\right] w_{m,n+1} + \left[\frac{2n-1}{2nU}\right] w_{m,n-1} + \frac{E}{U}\left[w_{m+1,n} + w_{m-1,n}\right] + \left[1 - \frac{2(E+1)}{U}\right] w_{m,n} \tag{6}$$

Where

$$U = \frac{(\Delta r)^2}{D_g \Delta t} \tag{7}$$

$$E = \frac{(\Delta r)^2}{(\Delta z)^2} \tag{8}$$

It was assumed in the boundary condition (*i.e.* equation 2) that there was no mass flow across the center axis. Thus, the predicted moisture content for a center element (m, 0) is:

$$w'_{m,0} = \frac{4}{U} w_{m,1} + \frac{E}{U}\left[w_{m+1,0} + w_{m-1,0}\right] + \left[1 - \frac{2(E+2)}{U}\right] w_{m,0} \tag{9}$$

At the top surface of the grain bin, the predicted moisture content of an element (M, n) is:

$$\begin{aligned} w'_{M,n} = {} & \left[\frac{2n+1}{2nU}\right] w_{M,n+1} + \left[\frac{2n-1}{2nU}\right] w_{M,n-1} + \frac{2E}{U}\left[WE + w_{M-1,n}\right] \\ & + \left[1 - \frac{2(2E+1)}{U}\right] w_{M,n} \end{aligned} \tag{10}$$

The equilibrium moisture content (WE) in equation (5) was calculated using Chung's equation (ASAE, 1985):

$$WE = B - F.\ln[-(T+C).\ln(RH)] \tag{11}$$

Where Chung's constants for corn are: B = 0.33872, F = 0.05897, C = 30.205°C.

The moisture content of an element at the wall is predicted by:

$$\begin{aligned} W'_{m,N} = {} & [\frac{8N+4}{(4N-1)U}]WE + [\frac{8N-4}{(4N-1)U}]W_{m,N-1} + \frac{E}{U}[W_{m+1,N} + W_{m-1,N}] \\ & + [1 - \frac{8N+4}{(4N-1)U} - \frac{8N-4}{(4N-1)U} - \frac{2E}{U}]W_{m,N} \end{aligned} \tag{12}$$

Following the same procedure, the equations for the five remaining elements, (0,0), (0,n), (M,0), (M,N), and (0,N), were developed similarly and reported by Abbouda (1984).

Adding the water generated from corn respiration further refined the previous model. The moisture generated was assumed to be equal to the percent of dry matter loss multiplied by 0.6, because oxidization of 1 gm of glucose release 0.6 gm of water theoretically. A similar kind of approach was used by Thompson (1972) in his study. The percent of dry matter loss was determined using the same equation as in the heat transfer model developed by Abbouda, *et al.* 1992a.

Materials and Methods

Four cylindrical, leak-proof steel bins of the same height (128 cm), but of two different diameters, were used and placed outdoors on concrete floor from March 6, 2001 to March 7, 2002 in the research station of King Faisal University, Al-Ahsa, Saudi Arabia. The diameters of the two bins were 142 cm and 76 cm, respectively.

Corn from the local market was divided into two lots. Lot 1 was originally with 12.00% moisture content and 46 °C temperature. Lot 2 was conditioned to 10.00% moisture content and 46 °C temperature. Two bins (a large one and a small one) were filled with corn from lot 1. The other two bins were filled with corn grains from lot 2. All bins were filled up to 112 cm height.

The measurement points for moisture in the radial direction were assigned for each bin. Measurement points were located at the radii of $r = 0$, 31.5, and 63 cm for the large bins, and 10 and 30 cm for the small bins (Fig. 1). There were 6 sampling points along the circle of each radius, except for $r = 0$. Therefore, at each cross-section, there were 13 points for the large bins and 12 points for the small bins. In the vertical axial direction, the measurement points were positioned at 8 cm, 61 cm and 104 cm above the bottom of the bin. The total number of sampling points was 39(13×3) for the large bins and 36 (12×3) for the small bins.

Samples were taken monthly at the locations described above with a 2 m probe. Each sample weighed 10 to 15 gm. The moisture contents were determined by drying corn at 103 °C for 72 hrs (ASAE, 1985).

In addition to monitoring moisture contents, microorganism invasion to the stored corn was evaluated. Samples from the three vertical locations were collected at the beginning of storage, at the selected time interval during storage and at the end of storage. Corn grains were microbiologically examined for total bacterial count, coliform count and molds and yeast count according to Speck, 1984.

Results and Discussion

Moisture Changes in Storage Bins:

Table 1 presented the average moisture contents for the four experimental bins at the end of tests. As mentioned early, there were 13 points at each cross-section for the large bins and 12 points for the small bins. The average in Table 1 was made by first taking weighted average of the points at each cross-section, then taking the linear average along the axial direction.

Table 1 indicated that grain lost moisture during storage. The average moisture content at the end of a one-year period dropped from 10.00% to 9.25% and from 12.00% to 9.84% for the small bins. Similarly for the large bins, moisture content dropped from 12.00% to 10.31% and from 10.00% to 9.60%. Bin size and initial moisture content significantly affected the moisture differences between the initial value and the final value. For the same size bin, the higher the initial moisture, the more moisture the grain would lose. If the initial moisture content was the same, the moisture reduction in small size bins was higher than that in the large bins on an average basis. In other words, the moisture in small size bins reaches equilibrium faster than that in large bins.

The typical monthly moisture contents in the small size bin filled with corn at 10.0 % IMC are shown in Figure 2. Each individual curve represents the average moisture at specific depth. The moisture content of corn at the top layer (about 8 cm thick) continued to drop after one month of storage and was significantly lower than other parts of the bin. Corn moisture content at the middle (61 cm above the bottom) lost much less moisture than the top layer. The corn at the bottom of the bin gained more moisture in the summer than other seasons and reached the maximum at the beginning and near the end of the experiment.

Figure 3 shows a typical trend between the average moisture contents and storage time for a large bin with different initial moisture content at different depths. At the top surface, the average moisture content was reduced about four points at the end of the experiment. The corn at the center lost much less moisture than the top layer. Therefore, a larger gradient existed at the top layer, which was about 8 cm thick.

Figure 4 presents the average moisture content at two radial distances for a small size bin with 12.0 % IMC. Obviously, the closer that grain was to the wall, the lower the moisture content. The data in the above three figures all indicated that moisture was not uniformly distributed within the bin. There were gradient existed both in the axial and radial directions. The gradient at the top layer was more pronounce than any other place. As storage progressed, the grain moisture contents at the top surface and near the wall were always lower than other parts.

Every biological material has its own hydroscopic property. It will create an equilibrium vapor pressure at a given temperature and moisture if the material is sealed in a container. When grain is exposed to air, it either gains or loses moisture depending on the vapor pressure difference between grains and air. If the vapor pressure of grains is higher than that of air, it will lose moisture and vice versa. In addition to gaining or losing moisture from air, biological material like corn also has its own respiration. If the amount of water generated from respiration cannot be diffused out, the local moisture content will also increase. As mentioned earlier, grain near the wall and below the top layer in all experimental bins lost higher moisture during storage than other positions. This is because the vapor pressure of grains in these positions is higher than that of air.

Quality Changes in Experimental Bins:

Grain deterioration may occur under inappropriate storage conditions. In this study, corn from all storage periods contained slightly high bacterial load, coliform count, and yeast and mold count (Table 2), which did not exceed the standard given by Speck (1984). It could be noticed that the corn after ten months of storage exhibited the highest microbial densities. This could be attributed to the grain moisture content (10.36%) compared with other storage periods. After one year of storage under unventilated conditioned, germination was slightly reduced from 91.4% to 76.8%.

Comparison of Measured and Predicted Moisture Contents:

Predicted and measured grain moisture contents near the surface (104 cm above the bottom), at 8 cm from the wall, and near the bottom (8 cm above the bottom) are plotted in Figures 5, 6, and 7, respectively for the large size bin containing corn at 10.00% IMC. The predicted moisture contents were from the mass transfer model developed by Abbouda, *et al*. (1992b). The standard error of estimate was 0.065 for corn near the surface, 0.10 for the corn at 8 cm from the wall, and 0.152 for the corn near the bottom of the bin. A close agreement between measured and predicted grain moisture contents indicated that the model and the parameter values used in the model are applicable for predicting moisture of stored corn grains under the local climatic conditions of Al-Ahsa, Saudi Arabia.

Conclusions

The grain lost moisture during storage. The average moisture content at the end of a one-year period dropped from 10.00% to 9.25% and from 12.00% to 9.84% for the small bins. For the large bins, moisture content dropped from 12.00% to 10.31% and from 10.00% to 9.60%.

The bin size and initial moisture content caused a significant effect on the moisture content during storage. The small bin lost more moisture than the large bin over the year. For the same size bin, corn grains with higher initial moisture content lost more moisture than that of lower initial moisture content.

Moisture profiles within each individual bin indicated that moisture gradients existed both in radial and in axial directions. In the radial direction, the moisture contents of stored corn were low near the container wall than at the center. In the axial direction, corn at the top surface had much lower moisture content than that below the surface layer. The fast moisture change near the wall and at the top surface was due to the fast heat transfer by natural convection.

Corn grains from all storage periods contained slightly high microbial count, which did not exceed the scientific standard. After ten months of storage, the corn grains exhibited the highest microbial densities, which attributed to the high grain moisture content.

The corn moisture content predicted by the mass transfer model agreed very well with measured moisture in the experimental bin. Thus, the model developed by Abbouda, et al. (1992b) and the parameter values used in the model are applicable for predicting moisture of unventilated stored grain under the climatic conditions of Al-Ahsa, Saudi Arabia.

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Nomenclature

B	constant in Chung's equation.
C	constant in Chung's equation.
D_g	mass transfer coefficient of moisture through grain (m^2/s).
E	dimensionless modulus.
F	constant in Chung's equation.
H	height of wheat in the bin (112 cm).
m	identification number of spatial element in axial direction.
M	identification number of spatial element at top surface of grain.
n	identification number of spatial element in radial direction.
N	identification number of spatial element at wall surface.
o	identification number of spatial element at the bin center.
r	radial distance (m).
R	radius of the bin (m).
RH	relative humidity (fraction).
t	time (s).

T	ambient air temperature (°C).
U	dimensionless modulus.
$w_{m,n}$	moisture content of grain at time t (fraction in dry basis).
$w'_{m,n}$	moisture content of grain at time "t + Δt" (fraction in dry basis).
WE	equilibrium moisture content (fraction in dry basis).
z	axial distance (m).

GREEK

Δ	finite-difference increment.
θ	angle of bin sector (rad)

Table (1)

Effect of bin size and initial moisture content on average moisture of stored corn after one year*

Bin Size	**Moisture contents of corn (%)**		**Moisture Difference (%)**	**Overall Moisture Decrease (%)**
	Initial	**Final**		
Large	12	10.31 a+	1.69	14
Small	12	9.84 b	2.16	18
Large	10	9.60 c	0.40	4
Small	10	9.25 d	0.75	7.5

*Duncan's Multiple Range Test.

+Means in a column with the same letter are not significantly different at p = 0.05 level.

Table (2)
Microbiological Properties of Stored Corn

	Storage Time (months)						
	0	2	4	6	8	10	12
Aerobic plate count Count $\times 10^3$ per gram	8.5	10.3	10.5	11.7	22.4	38.2	38.0
Coliform count count $\times 10^2$ per gram	3.7	5.4	9.8	14.1	36.3	195.3	190.3
Mold and yeast count count $\times 10^2$ per gram	1.5	1.9	3.7	4.5	7.3	8.5	8.2
Grain moisture %	10.00	9.45	8.61	9.05	10.27	10.36	10.31

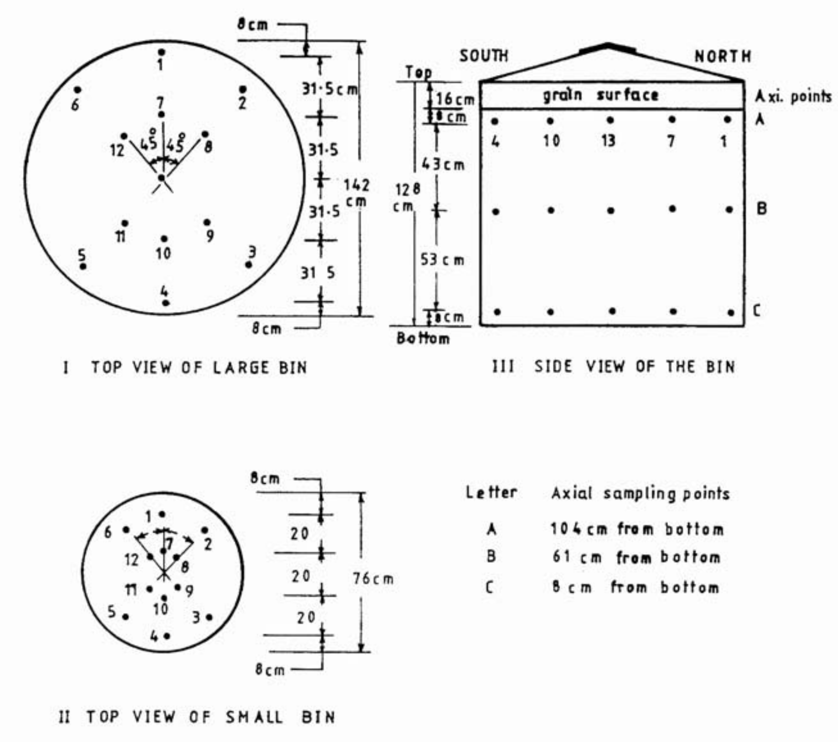

Fig 1. Location of sampling points in the experimental bins.

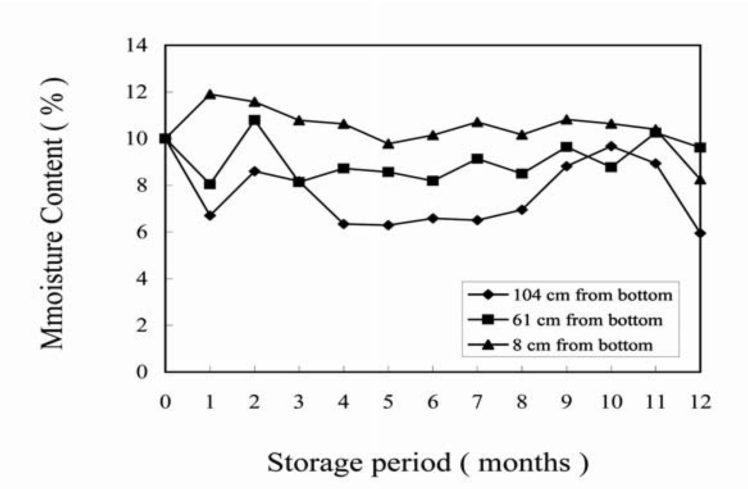

Fig 2. Monthly average moisture content vs. time at different vertical locations inside the small bin filled with corn at 10.0% IMC.

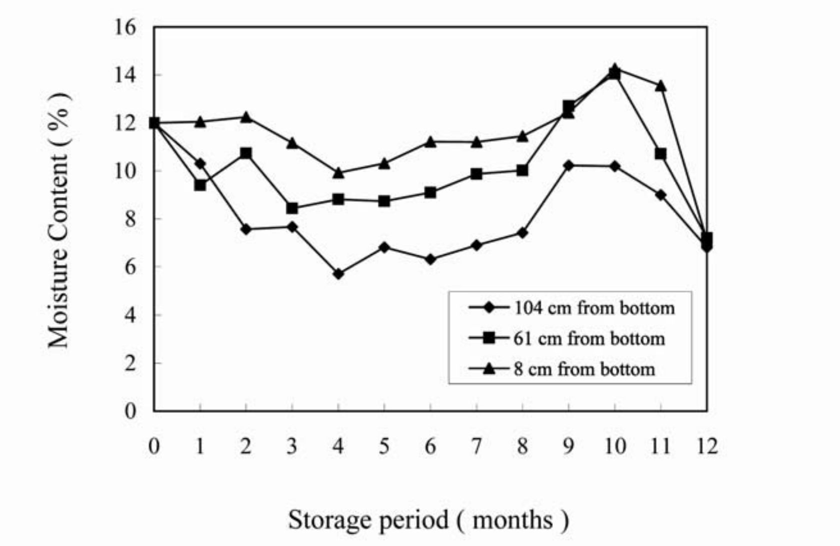

Fig 3. Monthly average moisture content vs. time at different vertical locations inside the large bin filled with wheat at 12.0% IMC.

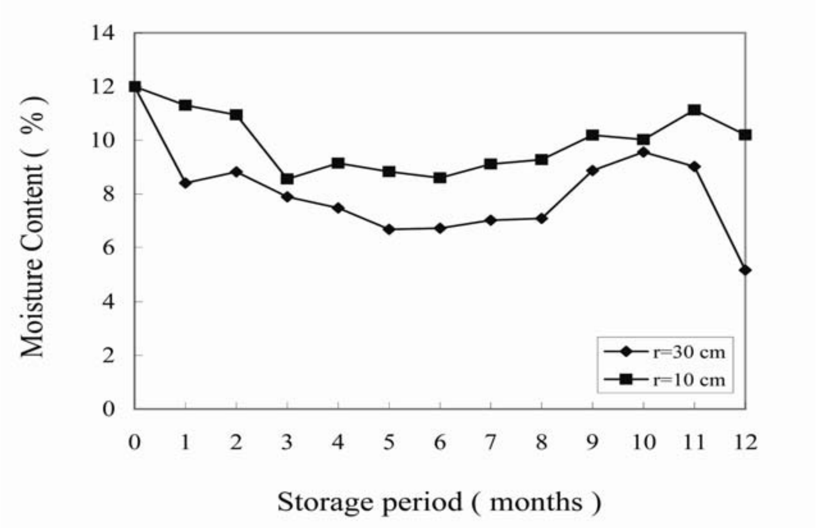

Fig 4. Monthly average moisture content vs. time at two radial positions inside the small bin filled with corn at 12.0% IMC

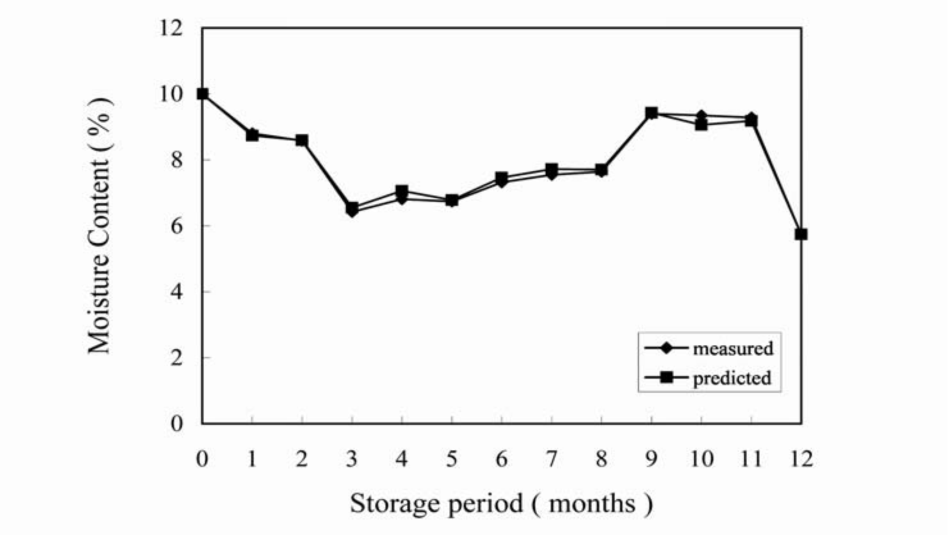

Fig 5. Predicted and measured moisture contents near the surface of the large bin containing corn at 10.0% IMC

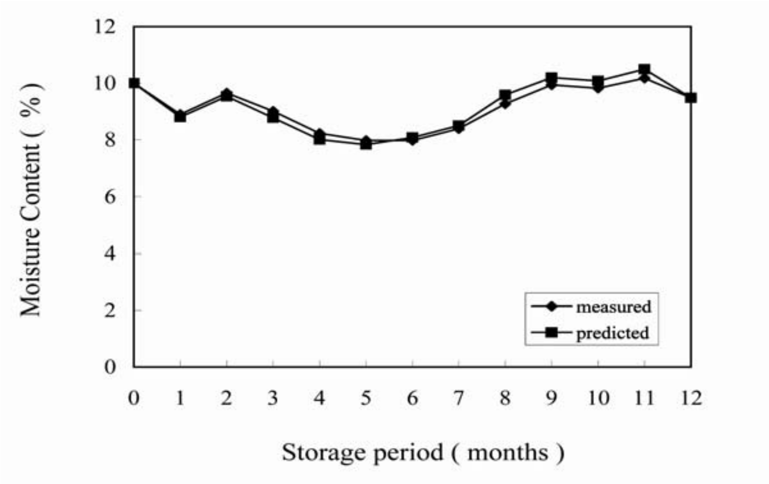

Fig 6. Predicted and measured moisture contents at 8 cm from the wall of the large bin containing corn at 10.0% IMC.

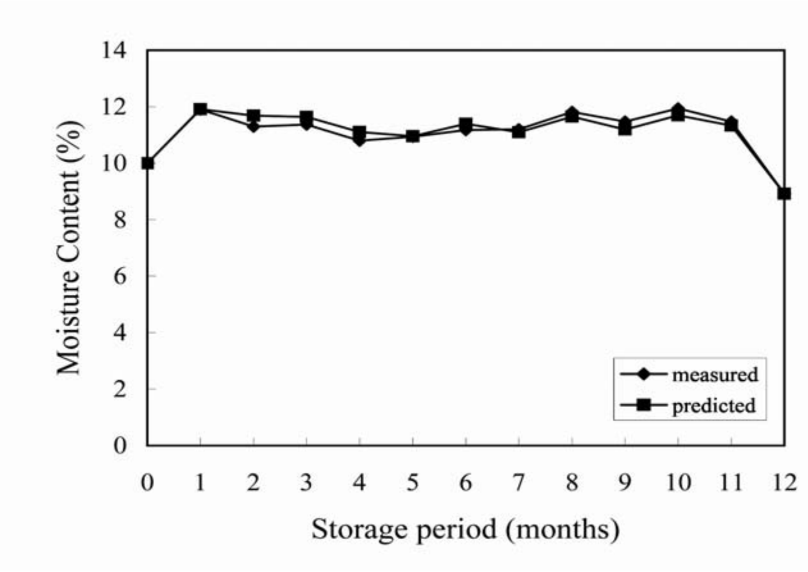

Fig 7. Predicted and measured moisture contents near the bottom of the large bin containing corn at 10.0% IMC.

تطبيق نموذج إنتقال الكتلة لمحاكاة التنبؤ بتوزيع المحتوى الرطوبي للذرة الشامية المخزّنة

علي بن مفرح العمري و سر الختم خلف الله عبودة

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الأحساء - المملكة العربية السعودية

الملخص:

النموذج الرياضي الثنائي البعد ذو الفرق المتناهي الذي أستنبط بواسطة عبوده وآخرون (١٩٩٢م) قد طبق في هذه الدراسة لمحاكاة توزيع المحتوى الرطوبي للذرة الشامية المخزنة في صوامع من الحديد أسطوانية الشكل . كما غذّيت جزيئات الرطوبة المنتجة بواسطة تنفس الذرة إلى هذا النموذج . ومن ثمّ تمت مقارنة الرطوبة المحسوبة بهذا النموذج بتلك التي جمعت من التجارب العملية لهذه الدراسة .حيث وجد أنّ هناك تقارباً شديداً بين مقدار رطوبة الذرة الشامية المقاسة فعلياً والمحاكاة بالنموذج الرياضي لتجربة استمرت لمدة عام . هذه النتائج أثبتت أنّ النموذج الرياضي وقيم المعلومات التي أستخدمت فيه يمكن تطبيقها لحساب المحتوى الرطوبي للذرة الشامية تحت ظروف التخزين بدون تهوية .

وقد وجد أنّ الذرة المخزنة قد فقدت محتوى رطوبي أثناء التخزين حيث كان متوسط المحتوى الرطوبي عند نهاية التجربة قد انخفض من ١٠٪ إلى ٩,٢٥٪ ومن ١٢٪ إلى ٩,٨٤٪ في الصوامع الصغيرة . أما بالنسبة للصوامع الكبيرة فإنّ المحتوى الرطوبي قد انخفض من ١٢٪ إلى ١٠,٣١٪ ومن ١٠٪ إلى ٩,٦٪ . هذه النتائج أوضحت أنّ حجم الصومعة والمحتوى الرطوبي الإبتدائي للذرة قد أثّر معنوياً على رطوبة وجودة الذرة المخزّنة تحت ظروف التخزين بدون تهوية في منطقة الأحساء من المملكة العربية السعودية.