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Mathemtical Simulation Model to Predict Storage Time of Grain

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Abstract. In this study, a mathematical simulation model for grain storage was developed. The model predicts the average temperature and changes in the moisture content inside the grain storage bin during the natural aeration. The model also predicts the allowable storage time for the different type of corn hybrids (resistant and susceptible). The model can predict the previous variables for any storage year after introducing its weather data.

The model is valid for just corn. It can be used for other grain types after obtaining their experimental equations of physical properties. Storage time at different conditions was estimated after calculating many multipliers such as temperature multiplier, moisture multiplier, damage multiplier, harvest multiplier, and hybrid multiplier. The program has been validated and calibrated by comparing the simulated results with the experimental field results.

Introduction

Computer simulation of grain storage can predict what results will be obtained when grain is stored under a defined set of conditions. Computer simulation consists of computer programs using mathematical models. It can, in a few seconds, predict results which would take weeks to compute by hand or years to obtain by experimentation.

Few models have been developed to predict the storage time of grain, and most of them have related to grain drying.

Wilcke and Bern [1] developed the NADWIS computer simulation model at Iowa State University. This model predicts average grain moisture, grain temperature, and grain deterioration of shelled corn during drying. This model was based on

Van Ee's [2] model (FALDRY), and Morey *et al.* model [3] which had their roots in Thompson *et al.* [4] storage model.

Friday *et al.* [5] studied the effect of corn hybrid on the production of carbon dioxide (CO_2) during storage of high-moisture shelled corn. They selected two corn hybrids, one was FR35 × FR20 as a fungi-resistant corn hybrid and the other was DF20 × DF12 as a fungi-susceptible hybrid. They found that the production of CO_2 in the susceptible hybrid was significantly different from that of the resistant hybrid.

Al-Yahya *et al.* [6] developed a computer model simulating the effect of hybrid traits and of fungicide treatments on fungal development in the high-moisture corn. The model predicts dry matter loss and minimum airflow requirements for both resistant and susceptible corn hybrids treated with various fungicide and dried with natural air.

Previous models did not provide the direct prediction of storage time. Thus comes the need of developing generic storage model. The developed model will be similar to those previously developed, but it will provide the direct prediction of storage time. Additionally, this model will predict storage time for each hybrid stated in Friday's study. The ultimate goal of developing this model is to predict the storage time of different corn hybrids. This information should be of great benefit to the grain farmers and grain industries.

List of Symbols

DM	=	dry matter decomposition.
t	=	storage time at the reference conditions.
T	=	estimated time to produce a given amount of CO_2 in hours.
T_R	=	time to produce the CO_2 at reference conditions (hr).
M_T	=	temperature multiplier.
M_M	=	moisture multiplier.
M_D	=	damage multiplier.
M_H	=	harvest moisture multiplier.
M_{HYD}	=	hybrid multiplier.
T_c	=	corn temperature, deg F.
M	=	moisture content, % w.b.
M_{DB}	=	moisture content, % dry basis.

D	=	mechanical damage, percent by weight.
Hm	=	harvest moisture.
T_f	=	final grain temperature.
GE	=	Te = equilibrium of grain and air temperature.
C	=	specific heat of corn.
L	=	latent heat of water in corn.
H_o	=	initial absolute humidity, 1b of water/1b of air.
T_i	=	initial air temperature.
H_f	=	final absolute humidity, 1b of water/1b of air.
ΔH	=	change in absolute humidity, 1b of water/1b of air.
Mo	=	initial moisture content, dry basis.
R	=	dry matter-to-air ratio, 1b dry matter per 1b air.
WG	=	weight of corn per layer $1b/ft^2$.
ΔX	=	layer thickness, ft.
WA	=	weight of air flowing through 1 ft^2 of layer for time. interval t, $1b/ft^2$.
Δt	=	time interval, hr.
Air	=	ventilation rate, cfm/ft^2.
V_A	=	specific volume, ft/1b air.

Simulation Model Definition

A mathematical simulation model for grain storage was developed to predict temperature, moisture changes, and storage time of different corn hybrids (susceptible and resistant) stored at high moisture content.

Deep bed simulation (DBS) is assumed here. DBS consists of a group of many thin layers of grain with air blowing up through the grain. The model will be developed to use official weather data (dry bulb temperature and absolute humidity) as input data.

Figure 1 shows the system diagram of simulation model for grain storage.

Model assumptions

True equilibrium will be obtained between the air and the grain for the time interval, t. The bin that will be modeled will be divided into several layers; each layer

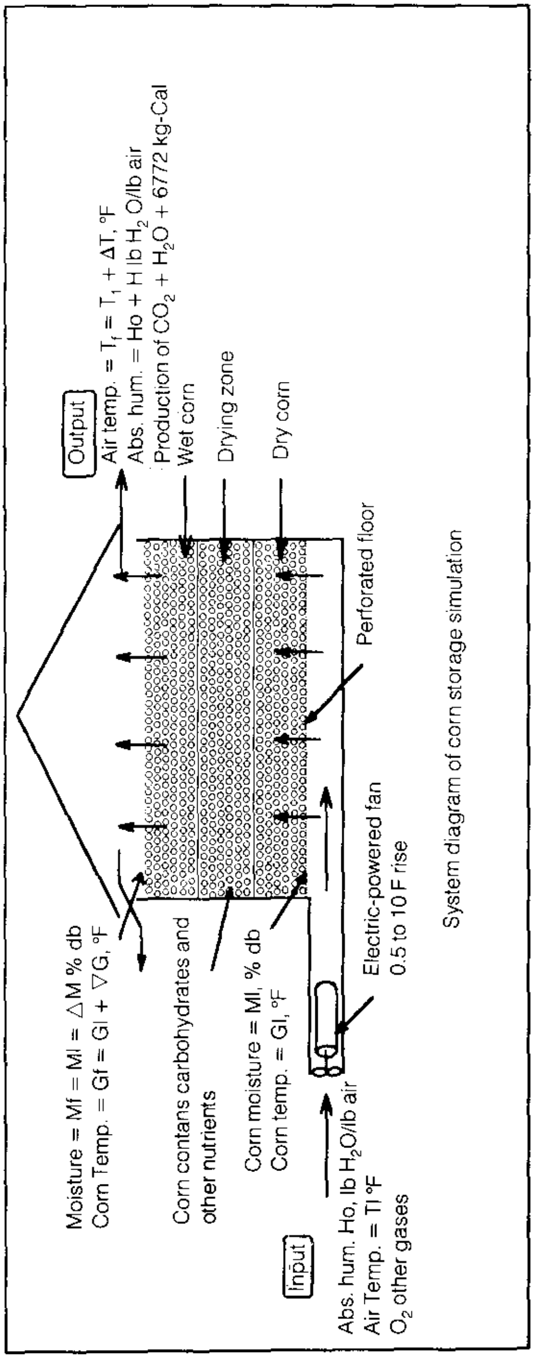

Fig. 1. Storage model system diagram.

will be dried in turn for a certain time period, beginning at the bottom. The exhaust air from one layer in the bed will be used as the input air to the next layer. There will be continuous aeration. There will be a tight storage bin equipped with a full perforated floor. There will be no supplemental heat, just natural air drying. Initial grain temperature will be equivalent to ambient air temperature. The model will be valid for just corn. It can be used for other grain types after obtaining their experimental equations of physical properties. Heating raised by the inlet fan will be neglected. There will be no heat gain or loss between bin walls and grain.

System parameters and input variables

System parameters and input variables are shown in Table 1.

Table 1. System parameters and their units

Parameter	Unit
Air flow	cfm/ft^2
Interval time	hr
Number of layers	#
Layer depth	ft
Ambient temp.	F
Absolute humidity	lb of water/1b of air
Harvest moisture	% wet basis
Storage initial moisture content	% wet basis
Hybrid type	resistant or susceptible
Percent of damage	%
Dry matter loss	%

Model output

The model will predict the following:

Average grain temperature among layers, average grain moisture among layers, and storage time of corn resistant and susceptible hybrids.

Variable and processing definitions

They are summarized in Table 2.

Table 2. Variable and processing definitions in the storage model

Variable	Definition
Dry matter decomposition	The index of grain rate deterioration. More than 0.5% dry matter loss will decrease the grading of corn.
Respiration	The complete combustion of a typical carbohydrate to produce CO_2, water, and energy
Temperature	Low temperature will have little effect on grain storability, whereas a higher temperature will increase grain rate deterioration.
Moisture	Higher grain moisture will effect grain storability, whereas low moisture might increase the time period of corn storage.
Air flow	Higher airflow may reduce corn spoilage due to removing hot spots within grain layers, whereas lower airflow may increase grain rate deterioration.
Grain multipliers	These include moisture, temperature, damage, harvest moisture, and hybrid multipliers. They will be used to calculate the equivalent reference condition storage times (60°F, 25% moisture content, wet basis (MCWB), and 30% damage).
Susceptible and resistant corn hybrids	These refer to how corn is resistant or susceptible to mold damage and spoilage.

Storage time under reference conditions

Steele [7] found that carbon dioxide production is related to storage time under reference conditions, (60°F, 25% MCWB, and 30% damage) by the equation:

$$DM = 0.0883\,(e^{0.006t} - 1) + 0.00102t, \tag{1}$$

where;

DM = dry matter decomposition, and
t = storage time at the reference conditions.

If the dry matter is known and storage time need to be calculated, then equation 1 can be reversed as follow:

$$t = 4.01347 + 600.5149\ DM - 347.718\ DM^2 + 110.716\ DM^3 - 13.6996\ DM^4 \quad (2)$$

Adjusted storage time to multipliers

Because the conditions of the grain will always differ from the reference conditions, Steele *et al.* [8] developed the following multipliers to calculate "equivalent reference storage times" within the formula:

$$T = T_R \times M_T \times M_M \times M_D \times M_H \times M_{HYD}, \quad (3)$$

where:

T = estimated time to produce a given amount of CO_2 in hours,
T_R = time to produce the CO_2 at reference conditions (hr),
M_T = temperature multiplier,
M_M = moisture multiplier,
M_D = damage multiplier,
M_H = Harvest moisture multiplier, and
M_{HYD} = hybrid multiplier (this variable was added in this model).

Multipliers equations

Estimated time to produce a given amount of CO_2

From equation 1, it was about 231 hours when the dry matter loss is 0.5%; and about 352 hours when the dry matter loss is 1%.

Temperature multiplier

It will be calculated according to the following conditions:

For $T_c \leq 60°F$ or $M \leq 19\%$,

$$M_T = 32.3e^{-3.48\,(T/60)}, \quad (4)$$

where:

T_c = Corn temperature, deg F, and
M = Moisture content, % w.b.

For $T_c > 60°F$ and $19 < M < 28\%$

$$M_T = 32.3e^{-3.48(T_c/.3/60)} + [(M\text{-}19)/100]e^{0.61\,[(T_c\text{-}60)/60]} \tag{5}$$

For $T > 60°F$ and $M >= 28\%$,

$$M_T = 32.3e^{-3.48(T_c/60)} + 0.09e^{0.61[T_c\text{-}60/60]} \tag{6}$$

Moisture multiplier

Steele *et al.* [8] done their work to obtain moisture multiplier only for the following range:

For $13 < M < 35\%$,

$$M_M = 0.103\,[e^{455/(M_{DB})^{1.53}} - 0.00845M_{DB} + 1.558], \tag{7}$$

where:

M_{DB} = moisture content, % dry basis, and

$$M_{DB} = MCWB/\,(1 - MCWB) * 100 \tag{8}$$

If moisture content out of this range, calculation of moisture multiplier in the model will be invalid.

Mechanical damage multiplier

It will be calculated according to the following conditions:

$$0.1\%\ \text{dry matter loss} \quad M_D = 1.82\,e^{-0.0143D} \tag{9}$$

$$0.5\%\ \text{dry matter loss} \quad M_D = 2.08\,e^{-0.0239D} \tag{10}$$

$$1.0\%\ \text{dry matter loss} \quad M_D = 2.17\,e^{-0.0254D} \tag{11}$$

where D = Mechanical damage, percent by weight.

Harvest moisture multiplier

$$M_H = 3.94e - 0.051Hm, \tag{12}$$

where Hm = harvest moisture.

Hybrid multiplier

Friday *et al.* [5] conducted an experiment for predicting carbon dioxide production with both resistant and susceptible corn hybrids. They developed the following multipliers with each hybrid:

For hybrid of FR35 X FR20: (Resistant)

at 0.1% DM	$M_{HYD} = 1.3$
0.5% DM	$M_{HYD} = 1.57$
at 1.0% DM	$M_{HYD} = 1.57$

And for hybrid of DF20 X DF12: (Susceptible)

at 01% DM	$M_{HYD} = 0.85$
at 0.5% DM	$M_{HYD} = 1.01$
at 1.0% DM	$M_{HYD} = 1.08$

Weather data of any specific year can be used to predict storage time of every hybrid at different dry matter loss.

Grain temperautre and moisture changes will occur between the bin layers. These factors will affect storage time; therefore, their changes within the layers should be simulated. Final moisture content and grain temperature at the end of each layer will be calculated according to the following equations:

Final grain temperature

Thompson [9] came up with the following equation to calculate the final grain temperature. It was obtained after making heat balance between the air and the grain.

$$T_f \frac{(0.24 + 0.45Ho)\,Te - H(1060.8 + L + 32 - Ge) + C^*Ge}{0.24 + 0.45H_f + C} \tag{13}$$

where:

T_f = final grain temperature
Ge = Te = Equilibrium of grain and air temperature

$$Te = \frac{(0.24 + 0.45\,Ho)\,Ti + C^*Gi}{0.24 + 0.45H_f + C} \tag{14}$$

C = specific heat of corn

= $0.35 + 0.00851$ MCWB (15)

L = Latent heat of water in corn

= $1094 - 0.57T_i$ (16)

H_o = Initial absolute humidity, 1b of water/1b of air

T_i = Initial air temperature

H_f = final absolute humidity, 1b of water/1b of air. The following equation was used to determine final absolute humidity.

$$H_f = \frac{2^*H_o + 0.001}{2} \tag{17}$$

ΔH = change in absolute humidity, 1b of water/1b of air = $H_f - H_o$

Final grain moisture

Thompson [9] made a mass balance between the air and grain in order to calculate final grain moisture content and he obtained the following equation:

$$M_f = Mo - \frac{100 \times H}{R} \tag{18}$$

where:

Mo = Initial moisture content, dry basis

R = Dry matter-to-air ratio, 1b dry matter per 1b air

= WG/WA

WG = Weight of corn per layer $1b/ft^2$

= $(37.86)\Delta X/\ (1-0.01Mo)$ (19)

ΔX = layer thickness, ft

WA = weight of air flowing through 1 ft^2 of layer for time interval t, $1b/ft^2$

= $t(AIR)\ \Delta x\ 60/V_A$ (20)

Δt = Time interval, hr

Air = Ventilation rate, cfm/ft^2

V_A = specific volume, ft/1b air

= $0.0252 \times (T_i + 460) \times (1 + 1.6055 \times H_o)$ (21)

Program Description

A flow chart of the main program is shown in Fig. 2. The model has three major subroutines, excluding the main program. These subroutines are as follows:

The GTEMP subroutine

In this subroutine, final grain and air temperature and final grain moisture will be predicted for each layer. The values in each layer will be averaged to obtain one representative value among layers.

The STIME subroutine

In this subroutine, storage time under the reference conditions stated previously will be calculated. Additionally, the adjusted storage time using temperature, moisture, harvest moisture, and damage multipliers will then be predicted. Seasonal temperature and moisture have been used to calculate the moisture and temperature multipliers.

The HYBRID subroutine

In this subroutine, the storage time for different corn hybrids, resistant and susceptible hybrids, will be predicted at different grain dry matter loss values. Thus, the hybrid multiplier will be adding to the STIME subroutine in this subroutine.

All variables and terms are defined in the attached program listing.

Program Validation

The model has been validated and calibrated by comparing the simulated results with the experimental field results obtained by Friday [5] using different corn hybrids.

Conclusion

A mathematical simulation model was developed to predict changes in grain temperature and moisture content. The model was also able to predict grain storage time of different corn hybrids.

Results of simulated high moisture storage test indicated that the average moisture content decreased during the storage time due to the aeration of the bin. Changes in airflow rate during the storage process can seriously affect the perfor-

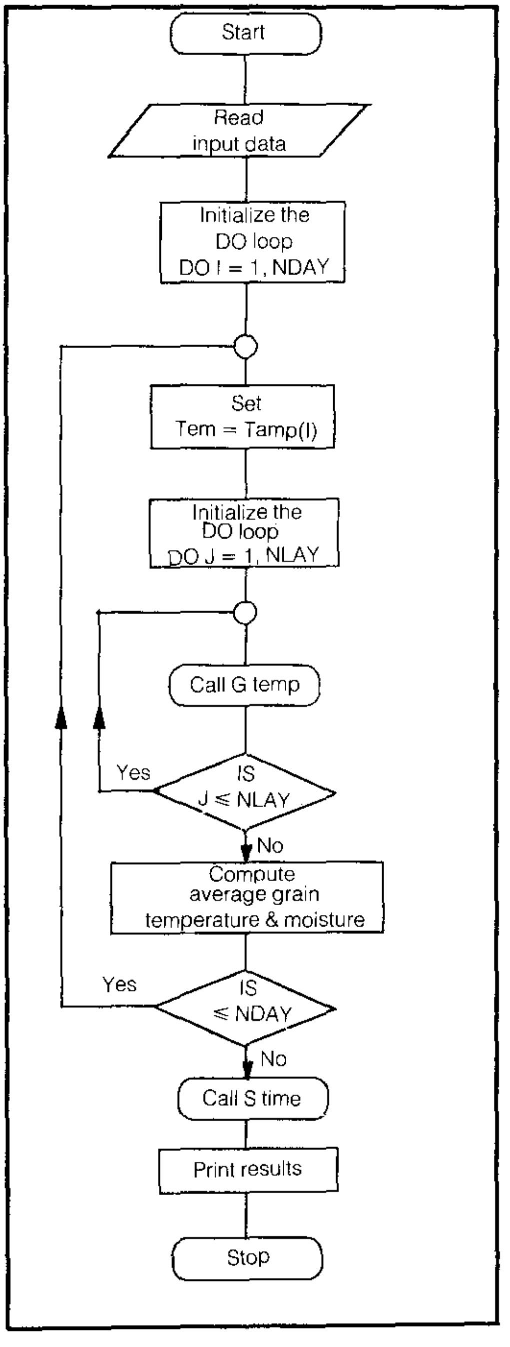

Fig. 2. Storage model flowchart.

mance of bin drying system. This model then can be used for predicting the drying of different types of corn hybrids at low temperature using unheated air with varying ambient conditions during the storage.

The average daily of grain temperature during storage period changed depending on the ambient temperature. When the air temperature was high, the grain temperature was increased.

At different dry matter loss levels, storage time of different corn hybrids was predicted. When the level of dry matter loss was high, the storage time increased. Storage time for resistant corn hybrid was longer than with susceptible hybrid through all levels of dry matter loss.

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برنامج محاكاة رياضي للتنبؤ بالعمر التخزيني للحبوب

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ملخص البحث. في هذه الدراسة تم تصميم برنامج محاكاة رياضي آلي لتخزين الحبوب. يتنبأ البرنامج بدرجة الحرارة المتوسطة والتغير في المحتوى الرطوبي داخل صومعة الحبوب المخزنة أثناء التهوية الطبيعية. كذلك يتنبأ البرنامج بالمدة المسموح بها لتخزين الذرة بصنفيها المقاوم والقابل للإصابة بالفطريات. يتنبأ البرنامج أيضًا بالمعلومات السابقة تحت ظروف أي سنة تخزينية استنادًا إلى قراءة بياناتها الجوية.

يصلح البرنامج فقط لمحصول الذرة ولكن بالإمكان استخدامه للحبوب الأخرى بعد الحصول على المعـادلات التجريبية المتعلقة بخواصها الطبيعية. تم تحديد العمر التخزيني عند الظروف المختلفة بعد حساب عدة عوامل ضرب مثل عامل درجة الحرارة والمحتوى الرطوبي ونسبة الكسر ورطوبة الحصاد والتغير في صنف الذرة. كما تم تحقيق ومعايرة البرنامج بمقارنة النتائج المتحصل عليها منه مع النتائج المتحصل عليها من التجارب العملية.