THE RESPONSE OF NON-VENTILATED GRAIN TO ENVIRONMENTAL TEMPERATURE

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Abstract

Warm damp grain, stored either in bags or in bulk is susceptible to deterioration. The rate of spoilage is increased locally by moisture migration that arises through convection currents induced by temperature gradients in the grain bulk. Moisture movement is exacerbated by biological activity arising from mould growth and insect activity, both of which are strongly temperature dependent. This paper uses a mathematical model of free convective processes to show how changing the physical size and configuration of bulks of stored grain, and changing the temperature of the environment in which the grain is stored affects moisture migration and grain quality. The mathematical model may be used as a grain storage management tool.

Introduction

Food grains are harvested seasonally but consumed continually. For this reason they must be stored for several months, and if buffer stocks are to be built up for times of poor harvests, grains may have to be stored for several years. When food grains are being stored they are liable to be destroyed by insect pests, mites, moulds, birds and rodents. In hot and humid regions biological activity is usually very intense and losses of food grains tend to be severe. For example, Agrawal and Singh (1981) report that losses of food grains in India between harvest and consumption are about 9%, and that insect pests appear to be the dominant cause of loss. A similar percentage of grain is destroyed during storage in most South East Asian countries; see for example Senanarong and Singhagajen (1981) and Shamsudin et al (1981). As a general rule insect activity and mould growth increase with both grain moisture and temperature.

In order to prevent stored grain from being ravaged by attack by moulds it is a sine qua non that it be dried to a level such that the relative humidity of the air in the intergranular voids is less than about 70%. Cooling of the grain below the optimum temperature range for insect population growth, namely 25-35°C, is also beneficial for long term storage.

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In this paper, a mathematical model of free convective heat and mass transfer processes in stored grain is briefly described. The model is then used as a management tool to calculate the rates of cooling of stacks of maize of different sizes and aspect ratios subjected to a range of environmental temperatures.

Mathematical model

The general approach to the mathematical modelling of free convection in porous hygroscopic media, such as cereal grains, has been described by Nguyen (1986). The basic assumptions made in the model are:

(1) the air and grain are in thermodynamic equilibrium at all points in the mass of stored grain.

(2) Boussinesq's approximation is valid, i.e. the variation of the density of the interstitial air with temperature is negligible except in the buoyancy term of the equation of motion.

(3) the air flow rate is sufficiently low for Darcy's law to apply

(4) the flow patterns are two-dimensional, hence end effects may be ignored.

In order to facilitate computation, a stream function ψ is introduced with $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$ and which is related to the vorticity of the motion.

In order that the results may be expressed in as general a way as possible the momentum, mass and energy balances may be written in dimensionless form thus:

$$\frac{f_c \kappa}{Pr\ \varepsilon\ L^2} \frac{\partial \zeta'}{\partial t'} = - Ra \frac{\partial T'}{\partial x'} - \zeta' \tag{1}$$

$$\nabla^2 \psi' = - \zeta' \tag{2}$$

$$\varepsilon \frac{\partial w}{\partial t'} + \gamma \frac{\partial w}{\partial t'} + u' \frac{\partial w}{\partial x'} + v' \frac{\partial w}{\partial y'} + \frac{L^2 \rho c_a}{k^*} R_W = 0 \tag{3}$$

$$\frac{\partial T'}{\partial t'} = \frac{c_a}{\gamma\ (c_m + c_w W)} \{- \frac{h_s}{c_a\ \Delta T} (u' \frac{\partial w}{\partial x'} + u' \frac{\partial w}{\partial y'})$$

$$- (1 + \frac{c_w}{c_a} w + \frac{w}{c_a} \frac{\partial h_v}{\partial T'})(u' \frac{\partial T'}{\partial x'} + v' \frac{\partial T'}{\partial y'})$$

$$+ \nabla^2 T' + \frac{L^2}{\gamma \Delta T k^*} R_T \} \qquad (4)$$

with $x' = x/L$; $y' = y/L$, $u' = uL\rho c_a/k^*$, $v' = vL\rho c_a/k^*$

and $T' - (T - T_1)/\Delta T$

The above equations account for the respiration of stored commodity. This phenomenon manifests itself in the equations by terms for the rates of liberation of water, R_W, and heat, R_T. R_W and R_T are empirical functions of time, grain moisture content and temperature (Thompson, 1972).

Expressions for the rate of decay of pesticides commonly applied to stored grains are given by Desmarchelier and Bengston (1979). The dimensionless concentration, $C'(=C/C_o)$ for a pesticide after a dimensionless time $\theta'(= t/\theta^*_{1/2})$ is given by

$$C' = \exp\,(-\,1.386\ r\ \theta' \times 10^{B'}) \qquad (5)$$

where r is the relative humidity of the air in the intergranular spaces and B' is a dimensionless temperature defined as B(T-30).

The above set of equations, boundary conditions, initial conditions and the appropriate constitutive equations comprise the mathematical statement of the problem. As a result of the non-linearities present and close coupling of the momentum, energy and mass equations, a numerical solution is necessary.

The governing equations were transformed into finite-difference equations by employing forward difference approximations for the time derivatives and central difference approximations for the spatial derivatives. The resulting finite-difference equations were then solved by the Samarskii-Andreyev Alternating Direction Implicit method. A combined Fourier Analysis - Fast Fourier Transform direct method was used to solve the elliptic Poisson equation.

Objectives of the numerical experiments

The mathematical model was used to conduct numerical experiments with the objective of investigating how changing the physical configuration of the stacks of stored grain and the storage temperature affects some aspects of the physical, biological and chemical behaviour of the stored grain. The independent variables chosen to drive the model are the height and aspect ratio (width/height) of the stacks of stored grain, and the temperature of the storage environment. It was possible to determine how changing these variables influenced the change with time of the temperature and moisture distributions in stored maize and the amount of loss of dry matter. The rates of decay of four chemical pesticides commonly applied to stored grain, namely malathion, methacrifos, fenitrothion and bioresmethrin were also investigated.

Results and discussion

The main features and results of the numerical experiments are shown in Table I. It can be seen that three aspects ratios, namely 0.5, 1 and 2 were studied, and the effects of two heights of the grain stack, 3m and 6 m, were investigated. Three initial grain moisture contents, 12%, 14% and 15% were studied together with a range of store temperatures from 15°C to 27.5°C. In each case the initial grain temperature is 30°C and the temperature of the floor is taken as 20°C. Rather than study each combination of independent variables, an ordered choice was made to highlight their effects on storing the grain for a period of 75 days.

Aspect ratio

Runs 2 and 5 exemplify the effect of aspect ratio on the cooling of the grain. As would be expected, the grain with the smaller aspect ratio (width 3m, height 6m) cools to a lower temperature because of its increased surface to volume ratio. After 75 days the mean temperatures of the stacks with aspect ratios 0.5 and 1 are 20.2°C and 24.1°C respectively. Figures 1(b) and 2(b) show the temperature contours in the two stacks. In the stack with the lower aspect ratio the temperature of the grain ranges from 15°C to 26.7°C. However, in the 6m x 6m stack of grain the maximum temperature is about 32.7°C, which is higher than the initial temperature because of respiration heating. Furthermore, the region of warm grain occupies a much larger volume than in the stack with the lower aspect ratio. For example, the proportions of grain with temperatures exceeding 24°C are 17% and 53% in the stores with aspect ratios of 1 and 0.5 respectively. It can be seen that the streamlines in Figure 2(a) are more closely spaced than in Figure 1(a) indicating higher air velocities hence a greater rate of cooling. As can be seen from figures 1(c) and 2(c) the maximum moisture contents of the grain in stacks with aspects ratios of both 0.5 and 1 is 0.19 (16% wb); this region of the 16% moisture content grain is somewhat more extensive in the stack with a smaller aspect ratio. The temperatures and moisture contents of the grain around the peripheries of both the 0.5 and 1.0 aspect ratio bulks are the same, hence the pesticide concentration around the edges of each bulk is equal. In the case of the commonly used pesticide, malathion, the concentration around the edge of the bulk is 0.86 that of the initial concentration. Figures 1(d) and 2(d) show the range and distributions of malathion concentrations in both bulks. The minimum concentrations in the bulks with aspect ratios 0.5 and 1 are 0.42 and 0.34 respectively, and their distributions reflect those of the temperature contours shown in Figures 1(b) and 2(b). The average dry matter loss in both stacks is small, i.e. 0.028% and 0.037% in the 0.5 and 1.0 aspect ratio stacks respectively.

It is to be expected that smaller stacks of grain will cool more quickly than larger stacks. The numerical results bear this out. Figure 3 shows the fall in average temperature of the two stacks studied in runs 2 and 7, i.e. these stacks both have an aspect ratio of 0.5 but heights of 6m and 3m respectively. After 75 days the mean temperatures of the large and small stacks are almost equal, but the temperature distributions within the grain are found to be slightly different. In the taller stack the warmer grain is closer to the upper surface of the grain, and occupies about three-quarters of the width of the bulk. In the smaller bulk the warmer grain is more evenly distributed along the central axis but it occupies less of the width of the store. The grain in the centre of the larger bulk is initially slower to cool down, and it is susceptible to respiration heating and liberation of moisture. This results in a rapid depletion of pesticide which affects the mean concentration of malathion as indicated in figure 4. The average dry matter loss of 0.028% in the larger stack of grain is some four times that of the smaller stack.

Initial grain moisture content

The rates of decay of pesticides and dry matter loss increase with increasing grain moisture content. Heat of respiration also increases with increasing moisture content which slows cooling, and this exacerbates the problem of pesticide decay and deterioration of grain quality. Figures 5 and 6 show how the mean grain temperature and pesticide concentration vary with time and moisture content. In the case of initially 15% moisture content grain the heat of respiration prevents much cooling. In fact, after 75 days the model predicts that grain in the centre of the bulk has increased to over 47°C, and the moisture content there is 20.2% wb. Needless to say, in this region of the grain the malathion concentration has fallen to 19%, and the concentration of methacrifos is 7% of its initial value. The dry matter loss is over 20 times greater in the initially 15% moisture content grain compared with grain initially at 12% moisture content.

Environment temperature

As an energy conservation measure it is preferable to maintain the temperature inside the grain store as close to ambient as possible. To investigate the affects of increasing the environmental temperature within the grain store numerical experiment 3 was repeated save that higher environmental temperatures were investigated. The results are summarized in Table I as runs 3, 10, 11 and 12 which correspond to environmental temperatures of 15°C, 20°C, 25°C and 27.5°C respectively. With an environmental temperature of 30°C the respiration heating caused the bulk to be destroyed by mould after 20 days or so. Although not apparent from Table I, the numerical results indicate that for the case when the environmental temperature is 25°C the maximum temperature in the grain has risen to 34.5°C; when the environmental temperature is 20°C the maximum grain temperature is 29°C.

Conclusions

A mathematical model of free convection in respiring maize has been outlined. The model may be used as a grain storage management tool to assess the optimal shape and size of stacks of grains required to minimize storage losses. The mathematical analysis also allows the effects of the temperature of the storage environment and the initial moisture content of the grain on storability to be investigated.

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Nomenclature

B	an empirical constant	1/°C
C	pesticide concentration	kg/m^3
c_a	specific heat of dry air at constant pressure	kJ/(kg dry air K)
C_o	initial pesticide concentration	kg/m^3
c_m	specific heat of dry grain	kJ/(kg dry grain K)
c_w	specific heat of liquid water	kJ/(kg water K)
f_c	effective conductivity factor = k^*/k_f	-
g	acceleration due to gravity	m/s^2
h	enthalpy of moist air	kJ/kg dry air
h_s	latent heat of vaporisation of water in grain	kJ/kg water
h_v	latent heat of vaporisation of free water	kJ/kg water
H	enthalpy of moist grain	kJ/kg
k^*	effective conductivity of packed bed	W/m/K
k_f	thermal conductivity of air	W/m/K
L	height of bed	m
p	pressure	Pa

P	density of grain (kernel density)	kg/m^3
Pr	fluid Prandtl number	-
R	heat of respiration	W/kg
Ra	modified Rayleigh number $= \dfrac{g\beta\rho^2 c_a}{\mu} \dfrac{\kappa}{k^*} \Delta T\, L$	-
R_T	rate of liberation of heat of respiration	kJ/kg/s
R_W	rate of liberation of moisture of respiration	kg/kg/s
t	time	s
T	temperature	K
T_1	temperature of cold wall	K
T_2	temperature of hot wall	K
u	velocity in x direction	m/s
v	velocity in y direction	m/s
V	filtration velocity	m/s
w	air moisture content	kg water/kg dry air
x,y	coordinates	
W	grain moisture content (dry basis)	kg water/kg dry grain
β	coefficient of volumetric expansion	1/K
ΔT	temperature difference $= T_2 - T_1$	K
ε	void fraction of packed bed	-
$\theta^*_{1/2}$	half-life of pesticide	s
κ	permeability of packed bed	m^2
ρ	density of air	kg/m^3
μ	viscosity of air	$N\ s/m^2$
γ	$= \dfrac{P(1 - \varepsilon)}{\rho\varepsilon}$	-
ζ	vorticity	1/s
ψ	stream function	-

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TABLE I

Run	Height m	Aspect ratio $\frac{\text{width}}{\text{height}}$	Initial m.c. temp.	Environment temp. °C.	Mean final temp. °C	Mean dry matter loss % x 10^2	Malathion	Methacrifos	Fenitrothion	Bioresmethrin
1	6	0.5	12	15	19.45	0.35	0.72	0.63	0.71	0.81
2	6	0.5	14	15	20.17	2.8	0.64	0.54	0.63	0.76
3	6	0.5	15	15	21.22	7.1	0.59	0.48	0.59	0.73
4	6	1.0	12	15	22.67	0.44	0.65	0.54	0.66	0.78
5	6	1.0	14	15	24.08	3.7	0.55	0.43	0.57	0.71
6	6	1.0	15	15	26.85	10.8	0.47	0.36	0.51	0.66
7	3	10.5	14	15	20.15	0.65	0.89	0.85	0.89	0.93
8	3	1.0	14	15	23.28	0.83	0.87	0.81	0.87	0.92
9	3	2.0	14	15	24.87	0.92	0.85	0.79	0.86	0.92
10	6	0.5	14	20	23.70	3.3	0.57	0.46	0.58	0.72
11	6	0.5	14	25	27.21	3.9	0.49	0.36	0.52	0.68
12	6	0.5	14	27.5	28.97	4.4	0.45	0.31	0.49	0.66

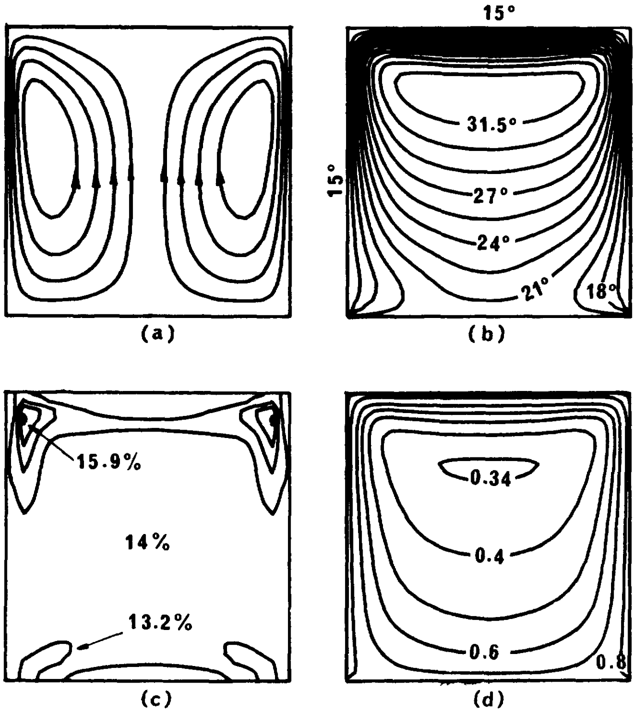

Figure 1(a) Streamlines, (b) isotherms, (c) moisture isosteres and (d) malathion isosteres in a 6m x 6m (i.e. aspect ratio 1) stack of corn initially at 30°C and 14% moisture content stored for 75 days in an environment at 15°C.

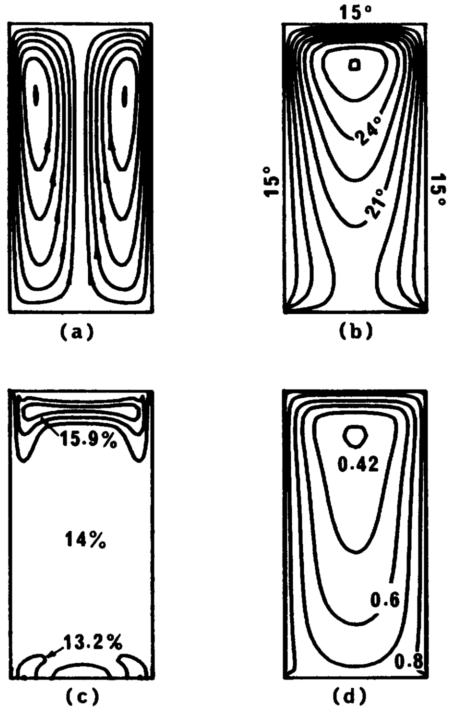

Figure 2(a) Streamlines, (b) isotherms, (c) moisture isosteres and (d) malathion isosteres in a 6m high by 3m wide (i.e. aspect ratio 0.5) stack of corn initially at 30°C and 14% moisture content stored for 75 days in an environment at 15°C.

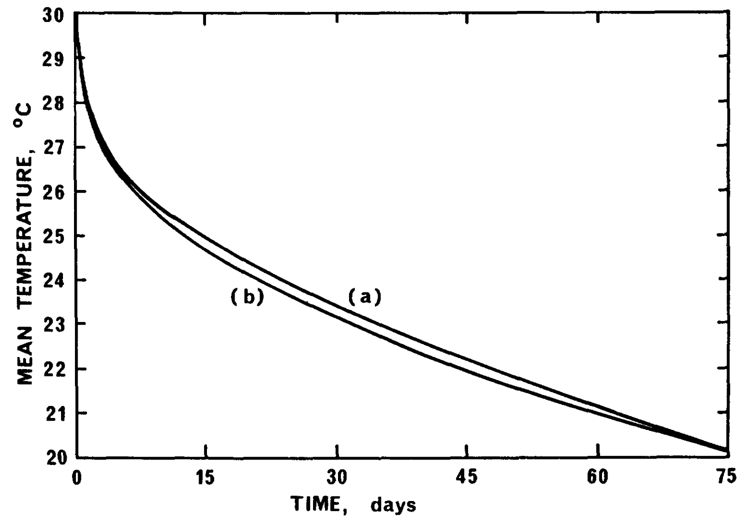

Figure 3 Mean temperatures in two stacks of corn, initially at 30°C and 14% moisture content exposed to an environmental temperature of 15°C. Both stacks have an aspect ratio of 0.5 and stack (a) is 6m high and stack (b) is 3m high.

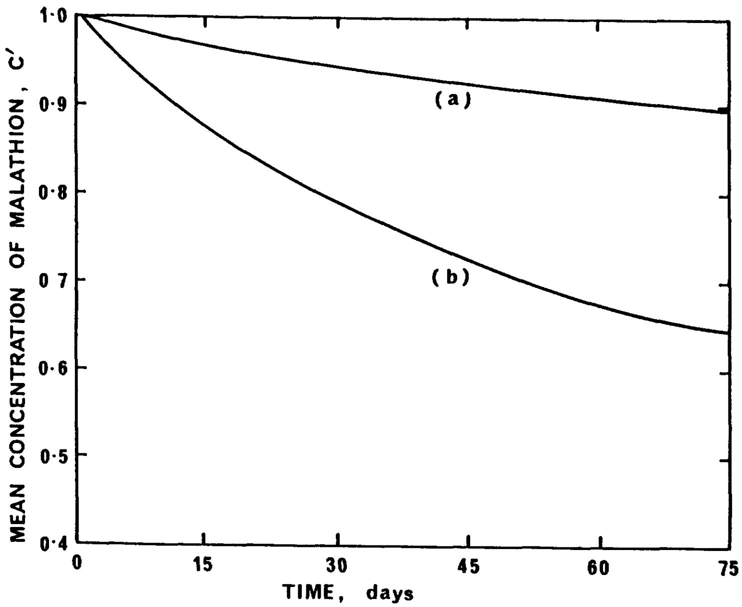

Figure 4. Mean concentration of malathion in two stacks of corn, initially at 30°C and 14% moisture content exposed to an environmental temperature of 15°C. Both stacks have an aspect ratio of 0.5 and stack (a) is 6m high and stack (b) is 3m high.

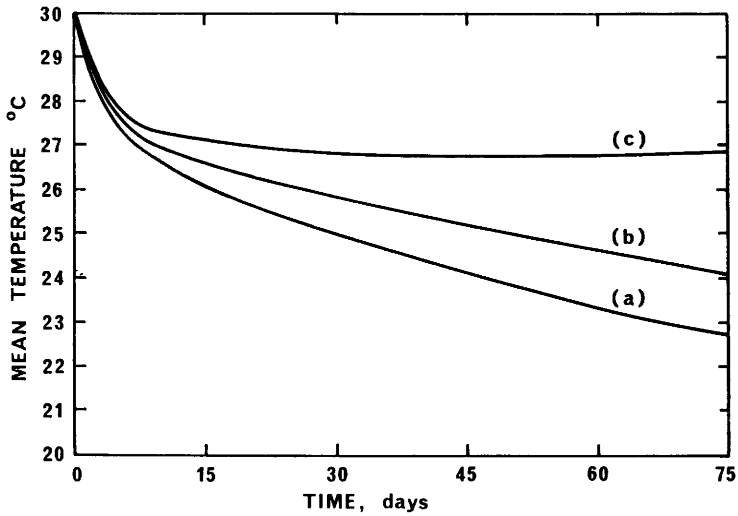

Figure 5. Mean temperatures of stacks of corn 6m high x 6m wide with an initial temperature of 30°C and exposed to an environmental temperature of 15°C. The initial moisture contents are (a) 12%, (b) 14% and (c) 15%.

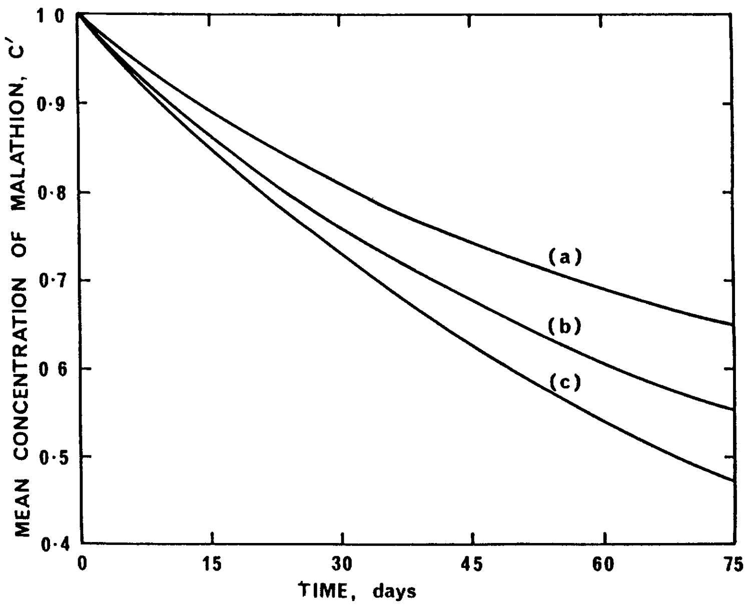

Figure 6. Mean concentrations of malathion in stacks of corn 6m high x 6m wide with an initial temperature of 30°C and exposed to an environmental temperature of 15°C. The initial moisture contents are (a) 12%, (b) 14% and (c) 15%.