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Soybean Seeds Mass Transfer Simulation during Drying Using Finite Element Method

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Abstract: Drying conditions affect the quality of dried soybean seeds. Therefore, an accurate description of the drying rate is required. In this study the finite element formulation and solution of diffusive moisture transfer equation was presented to improve seed drying simulation of axisymmetric bodies. The Fick's diffusive model was solved. For experiment, thin layer soybean seed, 'Villiamz' variety, was dried at drying air temperatures 30, 40, 50, 60 and 70°C with three replications at a fixed drying air velocity of 1 m/s. Good agreement was observed when the output of the model was compared to that of experimental data. The mean relative deviation mudulus (P) and modeling efficiency (EF) were used for comparing simulated and experimental data.

Key words: Soybean . Drying simulation . Finite element method . Model

INTRODUCTION

Soybean is the most important oilseed in the world market [1, 2]. Its importance in grain production has been increasing due to its high yield capacity and lower harvest cost in comparison to other grains [3]. Soybean has long been used as a primary protein source in human foods and animal diets. Soybean proteins are used as human foods in a variety of forms, such as infant formulas, flour, protein isolates and concentrates and textured fibers.

The moisture in grains after harvest must be reduced to a level acceptable for marketing, storage or processing. Soybean is usually harvested with moisture contents above the safe storage value. Hot air drying method is usually utilized to reduce the moisture content within the grain [4, 5]. However, the energy consumption is considerable and the air temperature is a sensible factor impacting the product quality although the higher air temperature enhances the moisture transportation from the grain [6, 7]. Dehydration or drying operations are important steps in storage and processing of grains [8]. The basic concept in drying of grains is the removal of water to a level at which microbial spoilage is minimized. Knowledge of the drying kinetics of soybean is essential for grain quality control during the drying process. Much work has been done to simulate the temperature, moisture content and stress distributions inside single grain kernels [9-16]. The mathematical models applied by these authors were similar but the geometrical models were somewhat different. This is an agreed principle that the temperature distribution within the geometrical model (spherical or cylindrical coordinate system) is not uniform. Simultaneous equations for moisture and heat diffusion are necessary to describe the moisture movement within agricultural products. The drying models presented by most researchers are very similar to the modified Luikov's equations used by Husain *et al*. [17]. Miketinac *et al*. [18] used the finite element method to solve the non-linear coupled systems of two partial-differential equations describing the thin layer drying process of grains and calculated the heat and mass transfer coefficients using the inverse method. Casada and Young [19] developed a model to predict heat and moisture transfer for long-term moisture migration of peanuts due to natural convection and diffusion in arbitrarily shaped porous media. Jia *et al*. [20, 21] performed simulation of temperature and moisture fields inside a maize kernel through finite element method. Yang *et al*. [22, 23] applied the finite element method to predict intra-kernel moisture content distribution during drying and tempering processes of rice and examined the relations between moisture content gradients and head rice yield trends during drying and tempering processes. Wu *et al*. [24] developed a mathematical model describing the simultaneous heat and mass transfer for a single kernel rice in the drying process.

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This study was conducted to develop the finite element formulation and solution of a set of coupled conductive heat and diffusive moisture transfer equations for a single soybean grain. The model considers the soybean as an axisymmetric body. The model was verified by the experimental data for a thin layer drying process.

MATERIALS AND METODS

Theoretical formulation and finite element analysis: For seed drying simulation, the Fick's diffusive equation describing the mass transfer process has been extensively applied [21, 23, 25, 26]:

$$\frac{\partial M}{\partial t} = \mathrm{div}(D\nabla M) \qquad (1)$$

where *M* is the moisture content d.b. (kg/kg); *D* is the diffusion coefficient (m^2/s); and t is the time (s). In moisture diffusion during the drying process, the surface of the seed exchanges heat with the environment by convection while the internal part is heated by conduction. If assuming that the moisture diffuses to the outer boundary of the seed in a liquid form and that the evaporation takes place at the surface of the seed, besides Eq. (1), the heat transfer equation for a single soybean grain should also be given as:

$$\rho c \frac{\partial T}{\partial t} = \mathrm{div}(k\nabla T) + L\rho \frac{\partial M}{\partial t} \qquad (2)$$

where ρ is the density (kg/m^3); *c* is the specific heat (J/kg K); *T* is the temperature (K); *k* is the thermal conductivity (W/m K); and *L* is the latent heat of vaporization of water (J/kg), all properties are given for a single seed. The initial conditions for the governing equations at t=0 are:

$$M(x,y) = M_0 \qquad (3)$$

$$T(x,y) = T_0 \qquad (4)$$

where *x* and *y* are directions and for t>0 the boundary conditions at the surface of the seed are:

$$D\left(\frac{\partial M}{\partial x} l_x + \frac{\partial M}{\partial y} l_y\right) + h_m\left(M - M_\infty\right) = 0 \qquad (5)$$

$$k\left(\frac{\partial T}{\partial x} l_x + \frac{\partial T}{\partial y} l_y\right) + h\left(T - T_\infty\right) = 0 \qquad (6)$$

where l_x, l_y are the direction cosines of the outward drawn normal to the boundary; h_m is the surface mass transfer coefficient (m/s); M_∞ is the moisture content of the ambient air d.b. (kg/kg); *h* is the convection heat transfer coefficient (W/m^2 K) and T_∞ is the ambient temperature (K).

To solve the problem, coupled heat and mass transfer governing equations (1 & 2) were taken into consideration but due to the importance of the simulation of the moisture change during the drying process of the seed, the result of the mass transfer governing equation (Eq. 1) is shown only. The assumptions for the drying model are: isotropic and homogeneous material, no shrinkage, liquid diffusion only and axisymmetric shape. The two-dimensional mathematical model is chosen so that the new coordinate form egg-shaped surfaces. Equation (1) was rewritten as:

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \qquad (7)$$

By applying the Gallerkin method and the boundary conditions, the forward finite difference approximation and, the triangular elements the differential Eqs. (1 & 2) are transformed into the following system of algebraic equations:

$$\left(K + \frac{C}{\Delta t}\right) M^{n+1} = \frac{C}{\Delta t} M^n + F \qquad (8)$$

where *K* is the element mass conductance matrix, *C* is the element mass capacitance matrix and *F* is the element mass force vector [27].

A computer program for a two-dimensional transient field problem such as the one described by Eq. (8) was written by Segerlind [27]. The effect of moisture content for each time step was modified for use in axially symmetric triangular elements. This program first solves Eq. 8 for given initial nodal values. For every time step Δt and a given set of nodal values $\{M\}_i$, a set of nodal moisture values $\{M\}_{i+1}$ are obtained and stored. A code was written in FORTRAN 90 to solve Eq. (8). Discretization of a single seed is shown in Fig. 1. Due to the symmetrical shape, only one quarter of a seed is shown. For clarity, the figure shows only 25 elements but in reality the number of elements increased to 1296 where no more significant change in the accuracy of the model was observed.

Sample preperation for thin layer drying experiments: 'Viliamz' variety of soybean was used in this study. Before conducting the experiment, moisture

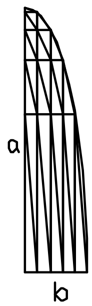

Fig. 1: Longitudinal cross section of one quarter of a single seed

content of soybean grains increased to a prespecified level by intermittently adding a calculated amount of distilled water to the seeds. Moistened samples were placed in sealed plastic containers and kept for at least 72 h in a cold store room at 10ºC to allow moisture to distribute inside the seeds while preventing any considerable microbial growth drum [28].

Drying equipment and experimental procedure: Dryer consisted of a fan, heaters, drying chamber and instruments for measurement. The airflow rate was adjusted by the fan speed control. The heating system consisted of an electric 4000 W heater placed inside the duct. The drying chamber temperature was adjusted by the heater power control. Two drying trays were placed inside the drying chamber. In the measurements of temperatures, thermocouples were used with a manually digital thermometer (Testo 925, Germany), with reading accuracy of 0.1ºC. A thermo hygrometer (Loutron HT-3005) was used to measure humidity levels at various locations of the system. The velocity of air passing through the system was measured by a hot wire (Testo, 405 V1, Germany). Experiments were performed to determine the effect of process variables on the thin layer drying characteristics of soybean. The variable considered was the drying air temperature. A series of experiments were designed to cover commercial drying of seeds. The experiments were conducted at five air temperatures (30, 40, 50, 60 and 70ºC), the air velocities was 1m/s. To decrease experimental error, each drying test was performed in triplicate. Therefore, 15 drying runs were carried out in a systematic manner.

Before the start of each drying run, samples of soybean were removed from refrigerator and placed in a plastic bag in the laboratory to bring the temperature of soybean to room temperature. Then the soybean were spread in a thin layer on drying trays and placed in the drying chamber and the test started. The ambient, drying air velocity and sample weight were continuously measured and recorded every 10 min during drying experiments, drying was continued until the moisture content (d.b.%) of the sample reached to that of the equiliberium moisture content. The average moisture content of the samples for each weighing period was calculated based on the initial mass and final moisture content of the samples. After each drying experiment, the sample was oven-dried 19 h at 130ºC to determine the moisture content [28]. The derived governing equations were used to simulate the drying process of a soybean seed. Results were compared to that given in the literature. Equations 1 and 2 were solved simultaneously but only the mass transfer results are presented. Experimental and theoretical results were compared to find the accuracy of the model. The simulation of soybean seed drying was compared with experimental results by the mean relative deviation mudulus (P) [29] and modeling efficiency (EF) [30] as followos:

$$\mathrm{MRD} = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{M_{pre,i} - M_{exp,i}}{M_{exp,i}}\right) \tag{9}$$

$$\mathrm{EF} = \frac{\sum_{i=1}^{n}(M_{exp,i} - M_{exp_{mean},i})^2 - \sum_{i=1}^{n}(M_{exp,i} - M_{pre,i})^2}{\sum_{i=1}^{n}(M_{exp,i} - M_{exp_{mean},i})^2} \tag{10}$$

where $M_{exp,i}$ is the nth experimentally observed moisture ratio, $M_{pre,i}$ the nth predicted moisture ratio and N the number of observations [31].

RESULTS AND DISCUSSION

Each grid consisted of 324, 3-noded elements, 181 nodes and time step of 1 min. Thin layers of soybean seeds were dried with similar drying conditions. During the drying process, moisture was measured every minute. Good agreement was observed when the output of model was compared to the experimental data. Modeling efficiency (EF) calculated for air temperatures of 30, 40, 50, 60 and 70°C were found to be 0.984, 0.986, 0.986, 0.988 and 0.993, respectively and that for the mean relative deviation mudulus (P), 2.17, 2.77, 3.20, 3.42 and 3.83, respectively. This result shows that simulation model is near to that of experimental data.

Figure 2 shows the comparison between the predicted mass average moisture content with the experimental data at 30, 40, 50, 60 and 70°C drying air temperature. For 30°C drying air temperature, up to 290 min, the model slightly underestimates the experimental data and after that a slight overestimation is observed. As temperature increases this time is increased as well

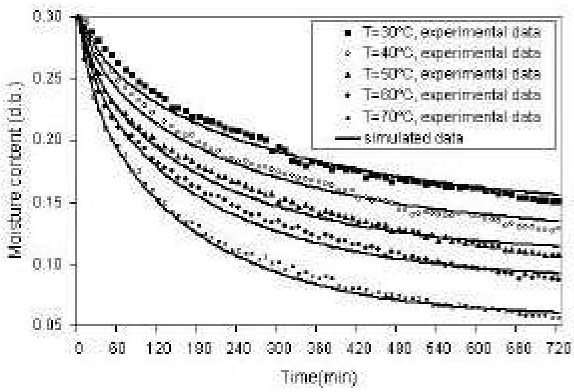

Fig. 2: Moisture content of soybean seed during drying. Mi=0.3% (d.b.)

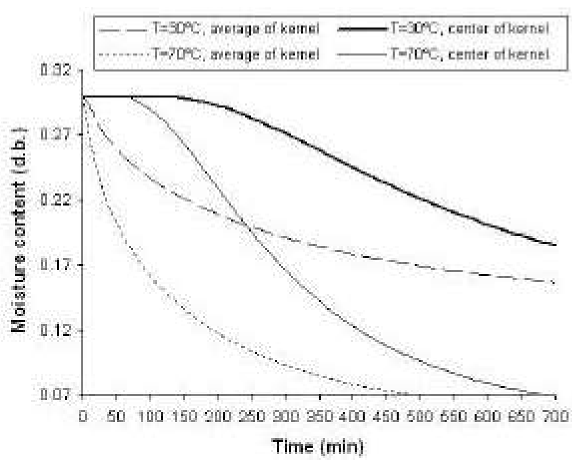

Fig. 3: Moisture content of soybean seed during drying. At the center and surface

where for 70°C drying air temperature, 530 min is elapsed before the underestimation changes to an overestimation (Fig. 2).

The simulated moisture curves at the center and for the seed as a whole grain for drying air temperatures 30 and 70°C are shown in Fig. 3. The center of seed moisture content reaches 0.2 (d.b.) for air temperatures of 30 and 70°C in about 600 (not shown in the Fig. 3) and 240 min, respectively, but the seed surface rapidly reaches 0.20 (d.b.) for air temperatures of 30 and 70°C in about 240 and 50 min, respectively (Fig. 3).

CONCLUSIONS

A computer program was developed and simulated the mass field within a single soybean seed. The simulation data are examined using values that were obtained from thin layer drying experiments with different drying air temperatures on 'Villiamz' variety soybean seed and the comparison shows that the simulation program gives good prediction in mass diffusion. Modeling efficiency (EF) for air temperatures of 30, 40, 50, 60 and 70°C were found to be 0.984, 0.986, 0.986, 0.988 and 0.993, respectively. This result shows that simulation model is near to that of experimental data. Therefore, the mass distribution inside the soybean seed during the drying process can be simulated reasonably by finite element method.

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