A Model for Estimating Loss of Wheat Seed Viability During Hot-Air Drying

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ABSTRACT

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A first-order kinetic model for estimating the loss of viability of wheat seeds during hot-air drying is presented. Model parameters were obtained by fitting the integral form of the model to grain germination percentage, moisture, temperature, and drying time. These data were determined throughout experimental drying in fluidized layers 0.08 m deep. Grain temperature varied continuously as in full-scale dryers. The Arrhenius activation energy E_a of the process was found to be 81.1×10^3 cal/mol, and the Arrhenius preactivation factor was determined to be a function of kernel moisture content. The model was compared with other experimental data, and the observed and predicted germination agreed within ±4.2 percentage points. The model will be useful in conjunction with drying simulation models to help in the design and operation of wheat dryers.

One of the main problems in commercial grain drying is keeping air temperatures within a range that does not reduce the quality of dried grains (Ghaly et al 1973, Nellist 1980, Schreiber et al 1981).

Viability of wheat seeds, expressed as a percentage of germination, was shown to be an appropriate parameter with which to measure the effect of thermal processes on grain properties such as seed viability (Lupano and Añón 1986) and flour quality (Schreiber et al 1981). The factors that influence the seed viability during hot-air drying are the history of the grain (initial germination), moisture content, temperature, and drying time (Roberts 1960, Nellist 1978, Schreiber et al 1981).

Under storage conditions of constant temperature and moisture, the germination percentage decreases with time according to a normal distribution curve (Roberts 1960). Nellist (1978) proposed this type of function for grain drying (temperature and moisture varying with time). He presented a calculation method in which drying was considered a succession of short time intervals; temperature and moisture remained constant within each interval. Loss of viability in each interval was calculated by means of the normal distribution function, which required the use of statistical parameters obtained from grain heating without evaporation.

Other authors (Schreiber et al 1981, Lupano and Añón 1986) have obtained kinetic models, based on experimental data, of viability losses during drying. Schreiber et al (1981) determined experimental germination percentages from samples taken during thin-layer drying of wheat at constant temperatures. They studied a wide range of grain temperatures and used a zero-order kinetic model to interpret the results. Lupano and Añón (1986) studied the effects of drying in a forced-convection oven on the properties of wheat germ proteins. They correlated the germination percentage as a function of the drying time using a first-order kinetic model, estimating a constant germ-drying temperature indirectly by differential scanning calorimetry.

The objective of this study was to develop a model to estimate the viability loss of wheat during drying under grain temperatures varying with time.

MATERIALS AND METHODS

Wheat

We used field-dried wheat (*Triticum aestivum*) variety Marcos Juarez-INTA, with moisture ranging from 0.12 to 0.15 (db) grown in Pergamino, Province of Buenos Aires, Argentina.

Moistening

Grains were moistened to predetermined levels by adding the necessary amount of water and by leaving them in closed containers for 48 hr, with ocassional stirring. Initial moistures before drying ranged from 0.24 to 0.33 (db). No viability loss due to moisturizing was detected.

Drying Procedure

Thick-layer fluidized bed drying was performed in a bench-scale batch dryer. With this system, both moisture and temperature are uniform throughout the grain at any given time because of the high degree of mixing, so representative samples from the bed can be taken (Hoebink and Rietema 1980, Giner and Calvelo 1987). Furthermore, if the bed height is above a certain minimum, it is possible to measure the grain temperature at the bed outlet and record it. The temperature of the inlet air was not recorded. Details concerning equipment and methods were given by Giner and Calvelo (1987). The grain temperature, the moisture, and germination percentage were determined as described below.

Temperature. In a fluidized bed, the difference between gas and solid temperatures decreases sharply with the distance from the base of the bed because of the high rate of heat transfer (Kunii and Levenspiel 1969, Hoebink and Rietema 1980, Giner and Calvelo 1987). If the bed height is great enough, the solid temperature can be considered equal to the air temperature at the bed outlet. The method described by Kunii and Levenspiel (1969) was used to calculate the minimum height ($H_{\min}$) required to determine the grain temperature with an error of 5% by measuring the air temperature of the bed outlet. We used the properties and parameters of wheat fluidization obtained in a previous study (Giner and Calvelo 1987). This led to $H_{\min} > 3.37/h_T$, where h_T is the air-to-particle heat-transfer coefficient.

To ensure a high enough value of $H_{\min}$, we used the lowest h_T value calculated by means of the three correlations described in the literature (Kunii and Levenspiel 1969, Pandey and Upadhyay 1981, Vazquez and Calvelo 1983). That value was $h_T = 130$ J/sec m^2 K (from the Vazquez and Calvelo correlation), which led to $H_{\min} > 0.026$ m. Bed heights of about 0.08 m (5 kg of wet grain) were used in the present study, allowing the grain temperature to be measured with an error of 0.1% as the temperature at the bed outlet. This temperature was measured and recorded continuously by a copper-constantan thermocouple recorder.

Moisture. Samples of 20–25 g were taken nine times during drying. Of each sample, 6–8 g were used for duplicate determinations of grain moisture (whole-grain method: 2 hr at 130°C in an air oven). Values were corrected to conform to the standard method of the Association of Official Analytical Chemists (1980) (ground grain: 1 hr at 130°C in an air oven) by using a previously obtained correlation (Giner and Calvelo 1987).

Germination percentage. The germination percentage was determined at 20°C in sterile petri dishes. Twenty-five seeds were placed in each dish on layers of filter paper. Two dishes (50 seeds) were seeded for each sample. Seeding was performed on the same day as the drying test; germinated seeds were counted at the end of day 3 (Lupano and Añón 1986).

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RESULTS AND DISCUSSION

Mathematical Interpretation of Experimental Data

Germination percentage data as a function of the drying time were fitted to a first-order kinetic model:

$$-\,\mathrm{d}G/\mathrm{d}t = kG\ , \tag{1}$$

where G = the percentage of germination, t = the time (min), and k = the kinetic constant (min^{-1}). If equation 1 is integrated between $t = 0$ and $t = t$, the following expression is obtained:

$$G = G_o \exp(-k\ t) \tag{2}$$

in which the dependence of viability on time and initial germination percentage (G_o) can be noticed.

The Arrhenius-type expression proposed for the effect of grain temperature on viability is:

$$k = \exp\left[-\frac{E_a}{R\ T_a} + \ln Z\right]\ , \tag{3}$$

where Z = the preexponential factor (min^{-1}), E_a = the activation energy corresponding to the viability loss during hot-air drying (cal/mol), T_a = the absolute temperature of grains, and R = the gas constant (cal/mol K).

Effect of moisture on viability during drying was taken into account by means of:

$$\ln Z = z_1 + z_2\ W\ , \tag{4}$$

where z_1 and z_2 = constants to be determined, and W = the moisture of the grains (db).

Activation energy was assumed to be independent of grain moisture content. This assumption was confirmed in preliminary fittings of the model, where E_a had been proposed as $E_a = e_1 + e_2/W$. The e_2/W term turned out to be negligible within the range of moistures usually present during wheat drying. Thus, the parameters of the model were E_1, z_1, and z_2.

If equations 3 and 4 are substituted in equation 2, the following expression is obtained:

$$\frac{G}{G_o} = \exp\left[-\exp\left(-\frac{E_a}{R\ T_a} + z_1 + z_2\ W\right) t\right]\ . \tag{5}$$

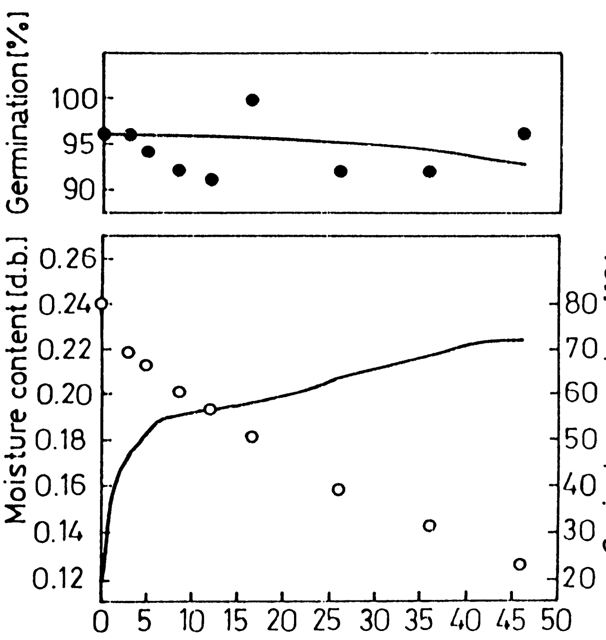

Fig. 1. Top: comparison of actual wheat germination data (●) with data predicted by the model (line) for a moderate fluidized bed drying condition. **Bottom:** grain temperature (○) and moisture content (line) drying histories.

This equation makes it possible to estimate germination G of seeds with initial germination G_o after an exposure time t, during which grain moisture and temperature (T_a) were kept constant. However, under actual drying conditions, both grain moisture and temperature vary with time. To enable equation 5 to be fitted to the experimental data, fitting was done over a succession of time intervals, Δt, in which grain moisture and temperature were considered constant. Equation 5 is then as follows:

$$\frac{G_t + \Delta t}{G_t} = \exp\left[-\exp\left(-\frac{E_a}{R\ T_{am}} + z_1 + z_2\ W_m\right) \Delta t\right]\ , \tag{6}$$

where G_t and $G_t + \Delta t$ are germinations at times t and $t + \Delta t$, respectively, and W_m and T_{am} are mean grain moisture and absolute temperature during the interval Δt.

Fitting of equation 6. To eliminate the typical oscillations of the germination data, monotonic curves were fitted to the germination experimental data by the least-squares method. Germination percentages were estimated by these curves at the experimental times for all seven tests. During the interval Δt, mean grain moisture (W_m) and temperature (T_{am}) data were obtained with the experimental values.

These data were fitted to equation 6 by using a SYSTAT statistics package (Wilkinson 1986) to minimize the sum of squares

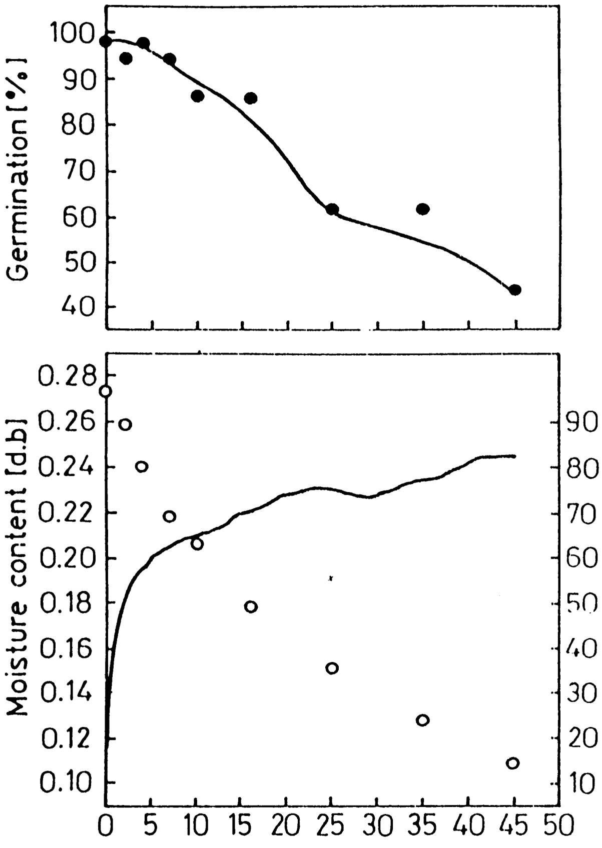

Fig. 2. Top: comparison of actual wheat germination data (●) with data predicted by model (line) for a drastic fluidized bed drying condition. **Bottom:** grain temperature (○) and moisture content (line) drying histories.

of the deviations. The coefficient value obtained for E_a was 81.1 $\times 10^3$ cal/mol, with a standard error of 10.7 $\times 10^3$ cal/mol.. For z, the best fit value was determined to be 104.6 ln(min^{-1}) with a standard error of 14.7 ln(min^{-1}). For z_2, the best fit value was 58.1 ln(min^{-1} kg of dry grain per kilogram of water), with a standard error of 7.0 ln(min^{-1} kg of dry grain per kilogram of water).

The nonlinear multiple correlation coefficient was 0.79, and the standard deviation of the estimate was 8.7 units of germination percentage.

Comparison of Predicted and Experimental Data

To test the model, two different drying tests (not used in the fitting of the model) were used. Figures 1 and 2 show the experimental data together with the predicted germination values. Histories of moisture and temperature are also presented. The standard deviation between predicted and observed values for these two tests was 4.2 percentage points of germination. The model satisfactorily estimated the loss of germination during drying.

Comparison of the Predictions of the Model with Data from Other Authors

Data from two drying tests from Lindberg and Sorensson (1959) were used to test the model and are shown in Figures 3 and 4. Histories of temperature and moisture are presented as well as the corresponding experimental values of germination percentage and the predictions of the model described in this article.

In spite of the differences attributable to the wheat varieties, the model estimated satisfactorily the time at which the decline of viability becomes appreciable. At longer drying times, the model predicted germination percentages lower than those shown by the experimental data.

Predictions of the "start of damage" time, based on Hutchinson's equation (Hutchinson 1944) are presented in Figures 3 and 4. The method (Nellist 1978) consists of adding fractions, each of which is the ratio between the time interval Δt and the maximum length of time to which grain can be exposed with no deterioration under those temperature and moisture conditions. When the sum of fractions reaches 1, the seed will start to lose viability if the treatment continues. In Figure 3, the value of 1 is reached for 4% viability loss, as predicted with the model (equation 6) presented in this article. In Figure 4, the same comparison corresponds to 5% of viability loss. Results show that the comparison between the two models is satisfactory.

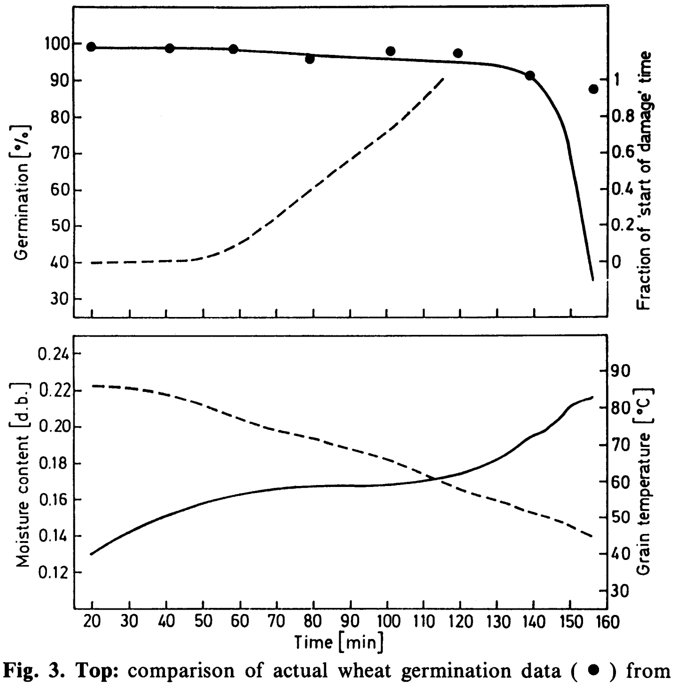

Fig. 3. Top: comparison of actual wheat germination data (●) from Lindberg and Sorensson (1959) with the data predicted by the model in the present paper (line) and with fractions of "start of damage" time predicted according to Hutchinson (1944) and Nellist (1978) (dashed line) for moderate drying conditions. **Bottom:** moisture (line) and temperature (dashed line) conditions used in the present study.

Simulations of the Effect of Grain Moisture and Temperature on Kinetic Constant

Figure 5 depicts the influence of grain moisture and temperature on the first-order kinetic constant, k (equation 3), which represents the rate of viability loss. At a given moisture content, the rate of damage increases sharply beyond a certain temperature. On the other hand, a decrease of moisture content shifts this effect toward higher temperatures.

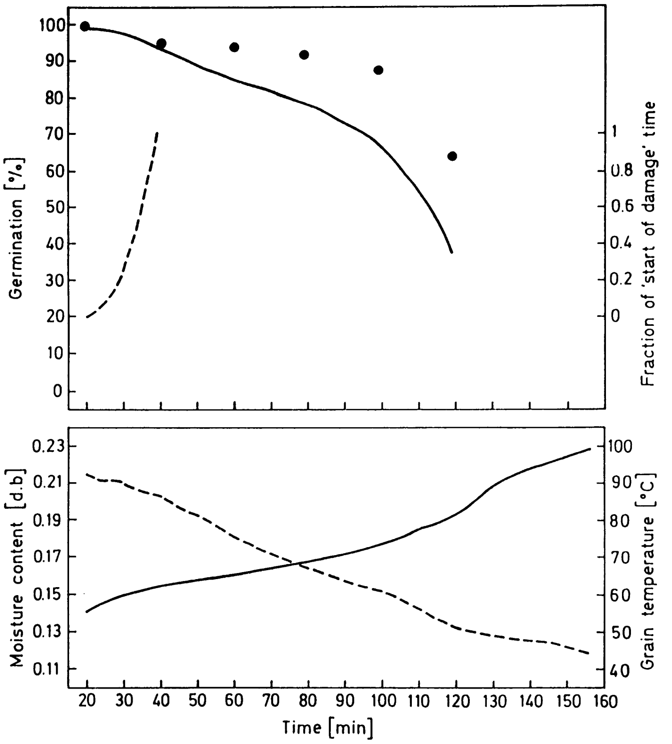

Fig. 4. Top: comparison of actual wheat germination data (●) from Lindberg and Sorensson (1959) with the predicted data of the model in the present paper (line) and with fractions of "start of damage" time predicted according to Hutchinson (1944) and Nellist (1978) (dashed line) for drastic drying conditions. **Bottom:** moisture (line) and temperature (dashed line) conditions used in the present study.

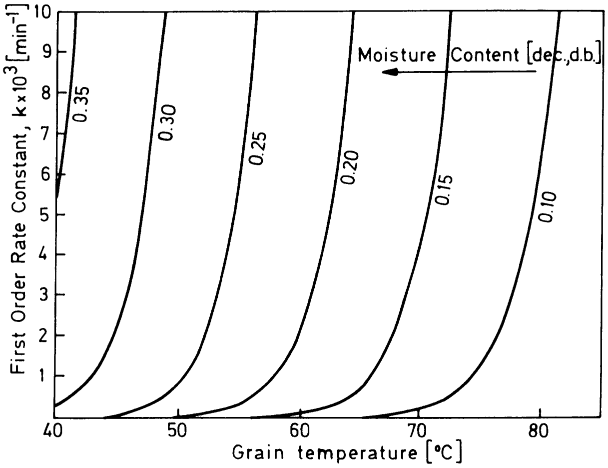

Fig. 5. First-order rate constant as a function of grain temperature for moisture content between 0.10 and 0.35 (db).

Possible Applications of the Model

The model (equation 6) could be applied—-within the range of time, moisture, and temperature used in this work—for estimating the loss of wheat viability during drying in the following ways:

1. Using experimental histories of moisture and temperature. Examples of such histories are shown in Figures 1–4.

2. Using moisture, temperature, and time values predicted by means of a simulation model of wheat dryers. This would be the most useful application of the model because there are experimentally proven drying models for different systems, such as static deep bed (Henderson and Henderson 1968, O'Callaghan et al 1971), continous cross-flow (Nellist 1987), and fluidized bed (Giner and Calvelo 1987). In this case, the model could be used to predict safe operating conditions for wheat drying.

CONCLUSIONS

A first-order kinetic model that estimates the loss of viability of wheat seeds throughout drying was developed. The model uses the temperature and moisture histories of grains. The Arrhenius equation was proposed for the variation of the kinetic constant with temperature; the preexponential factor was found to be a function of the grain moisture.

The predictions of the model show satisfactory agreement with the experimental germinations within the ranges of time, temperature, and moisture used in this study. However, further drying tests conducted under other conditions and with different wheat varieties should be analyzed before adopting this model to estimate safe operating conditions for wheat dryers.

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