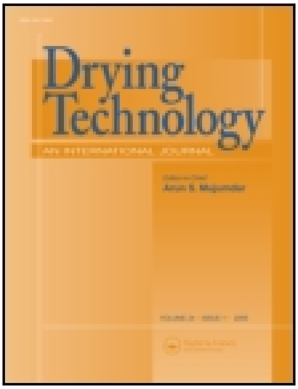


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# DRYING OF GELATINIZED WHOLE WHEAT

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# DRYING OF GELATINIZED WHOLE WHEAT

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## ABSTRACT

Whole grains of gelatinized durum and soft wheat were dried by forced and natural convection at 40, 60, 80, and 100°C. Magnetic resonance images taken periodically during drying indicated that Fick's diffusion is not applicable to describe the moisture transfer during drying of the gelatinized wheat grains. A simple mathematical model based on overall moisture balance fitted the experimental data very well. The drying took place in the falling rate period, which was approximated by two regions – first and second falling rate periods (FFRP and SFRP). The internal drying coefficient linearly increased with increasing drying temperature, and was almost an order of magnitude (from $10^4$ to $10^5$ $s^{-1}$) higher during FFRP than SFRP. The soft wheat dried faster than the durum wheat. The effect of forced convection was more pronounced during FFRP than SFRP.

*Key Words:* Bulgur; Diffusion; Durum; Instantized grain; Kinetics; Magnetic resonance imaging; Mass transfer; Soft wheat.

## INTRODUCTION

Gelatinization is one of the first steps in the manufacture of instantized grain products such as breakfast cereals. In many processes, gelatinized grain is subsequently dried. The drying method and conditions effectively determine type and characteristics of the final product. For example, high temperature convection-conduction drying gives a crunchy structure to the gelatinized wheat, but the low temperature convection drying renders the wheat hard. While the former wheat is suitable as a breakfast cereal, the latter is suitable for other food preparations.

Bulgur is an instant whole-wheat product, which is one of the staples in the Middle Eastern countries. Gelatinization, drying, and debranning are the primary steps in bulgur production. In traditional bulgur manufacture, wheat is gelatinized in water and dried in air. Best quality bulgur is produced from durum wheat, however soft wheat varieties are also used. Drying kinetics of gelatinized rice has been widely reported in the literature (Prasad et al., 1994; Byler et al., 1987; Chandra and Singh, 1984; Bakshi and Singh, 1982). However, information on drying kinetics of the gelatinized wheat relevant to manufacturing of instantized cereal products is not available.

The objective of this study was to determine the drying kinetics of whole durum and soft wheat gelatinized in water.



## THEORETICAL CONSIDERATIONS

Drying of high moisture foods is generally characterized by constant rate and falling rate periods. The constant rate period is observed only if a continuous film of moisture exists over the drying surface, and the moisture is continuously available for evaporation. In this case, the drying rate is controlled by the surface resistance (i.e. surface mass transfer coefficient), determined by the airflow rate used, rather than the internal resistance of the material being dried. At critical moisture content, the drying begins to occur in the falling rate period. During this, the internal material resistance is the rate limiting.

The drying rate (R, $kg/m^2 \cdot s$) during the falling rate period can be determined from:

$$R = -\frac{M_S}{A}\left(\frac{dX}{dt}\right) \tag{1}$$

where, $M_s$ = mass of dry solids (kg); A = drying area ($m^2$); X = dry basis moisture content (kg/kg dry solids); and t = time (s).

Fick's approach based on unsteady state mass transfer has been widely used for describing drying of foods during the falling rate period:

$$\frac{\partial X}{\partial t} = \nabla^2 DX \tag{2}$$

where D = moisture diffusivity.

Equation 2 can be solved numerically or analytically with appropriate initial and boundary conditions and certain assumptions, such as uniform initial moisture distribution within the grain (Bakshi and Singh, 1982). According to Fick's diffusion theory, moisture profile within the grain during drying increases from grain surface to the center along the spatial coordinates.

We used an unsteady state bulk mass transfer approach to describe the drying kinetics of the gelatinized wheat. This is based on mass balances for moisture loss for the whole grain and at the grain surface (drying air-grain surface interface). Moisture balance for the grain during drying can be expressed as:

$$k_i A(m_e - m) = V(dm/dt) \tag{3}$$

Where, $k_i$ = internal mass transfer coefficient (m/s), $m_e$ = equilibrium moisture concentration (kg $H_2O/m^3$); m = moisture concentration at time t (kg $H_2O/m^3$); and V = volume ($m^3$). Dividing both the right and left hand side of equation (3) by solids density ($\rho_s$, kg/$m^3$) will change the moisture concentration terms (m and $m_e$) into dry basis moisture contents (X and $X_e$):

$$K_i A(X_e - X) = V(dX/dt) \tag{4}$$

Integration of equation (3) results in:

$$\ln X^* = -K_i t \tag{5}$$

where, $X^* = (X - X_e)/(X_0 - X_e)$ = moisture ratio; $X_0$ = initial dry basis grain moisture content; $K_i = k_i/z_i$ = internal drying coefficient ($s^{-1}$); and $z_i = V/A$ characteristic dimension (m).

The moisture balance at the grain surface is written as:

$$k_s A(X_a - X_e) = V(dX/dt) \tag{6}$$

where, $k_s$ = surface mass transfer coefficient (m/s); $X_a$ = dry basis moisture content of drying air (i.e. absolute humidity). Integration of equation (6), with the assumption $X_e \gg X_a$, results in:

$$X = -K_s t \tag{7}$$

Where, $K_s = k_s X_e/z_i$ = surface drying coefficient ($s^{-1}$).

Since moisture loss at the surface is equal to moisture loss from the grain, setting equations (4) and (6) equal provides:

$$\frac{X - X_e}{X_e} = \frac{K_s}{K_i X_e} \tag{8}$$

The dimensionless ratio ($K_s/K_iX_e$) in equation (8) is termed as the "drying Biot number", $DB_i$. The $DB_i$ compares the relative values of the surface and internal resistances for moisture removal, and has the same physical meaning as Biot number ($B_i$). When $B_i > 0.1$, the surface resistance is negligible and the mass transfer is controlled by the internal resistance (Geankoplis, 1993).



## MATERIALS AND METHODS

### Sample Preparation

Durum (*Triticum durum*) and soft (*Triticum aestivum*) wheat samples (~100 kernels each) were cooked in distilled water at 100°C for one hour for complete of gelatinization of the wheat starch (Turham and Gunasekaran, 1999). The gelatinized samples were sealed in water vapor impermeable polyethylene bags and kept overnight at 4°C to ensure uniform moisture distribution within the kernels. Before the drying experiments, the samples were allowed to equilibrate to room temperature. Twenty whole grains of wheat were randomly selected and surface blotted with a soft tissue paper to remove the surface moisture and used for each drying experiment. Grain moisture contents were determined by oven drying at 105°C for 72 h. The initial moisture content of the gelatinized durum and soft wheat samples were 130 and 140% dry basis, respectively.

### Drying

The wheat samples were placed in stainless steel, wire-mesh containers (diameter = 30.2 mm; height = 27.7 mm). The samples were dried by both forced and natural convection. For forced convection, a laboratory bubble-bed dryer with a cylindrical bed (diameter = 32.3 mm; height = 450 mm) was used. The air velocity, measured using a hot-wire anemometer (Solomat MPM 500e, Flowery Branch, GA), ranged between 2.5-3.0 m/s. The air velocity was high enough to suspend the grains during drying. For natural convection drying, a programmable laboratory oven (Fisher Isotemp® 838F, Pittsburgh, PA) was used. Both forced and natural convection drying experiments were conducted at 40, 60, 80, and 100°C (absolute humidity of the drying air = 0.013 kg water/kg dry air). The sample mass was measured periodically during drying using an analytical balance (Mettler Toledo AG245, Columbus, OH).

### Magnetic Resonance Imaging

The moisture profiles within the grains were determined periodically during drying by means of magnetic resonance (MR) imaging. A Bruker DMX 400 spectrometer with a 9.4-T magnet was used. Single grains of wheat was positioned in the hole of a polyoxymethylene sample holder (8.5-mm $\times$ 15-mm) inserted into a 10-mm MR test tube. The gradient-refocusing imaging technique was used with an echo time (TE) of 11.4 ms and a repetition time (TR) of 50 ms. The proton signal was processed using an image processing software available with the spectrometer. MR images were acquired along the radial direction for individual wheat grains. The slice thickness was 0.8 mm; the field of view was $15 \times 15$ mm with matrix dimension of $256 \times 256$. Thus, the in-plane pixel resolution of the MR images was 0.059 mm.

## RESULTS AND DISCUSSION

The MR images showing moisture profiles during drying within the wheat kernel along the radial direction are presented in Figure 1. The "high" to "low" moisture content variation is qualitatively depicted by a pattern of colors from dark to light, respectively. The uneven color distribution in the MR images at $t = 0$ min implies that the radial moisture distribution was not uniform in the samples at the beginning of the experiments. This is contrary to the uniform initial moisture distribution assumption used in solving equation 2. The randomness of color distribution in the MR images at t>0 min indicates that moisture content decreased from the drying surface toward the center along the radial axis, but in a manner unlike what would be expected according to the Fick's model. This suggests that the Fick's diffusion theory might not represent the *actual distribution* of water within wheat grains during drying. Additional experiments are needed (with wheat and other grains) to reconfirm our observations that are counter to the widely accepted Fick's diffusion.

Drying rate vs. moisture content plots (not shown) indicated that the drying of gelatinized wheat was in the falling rate period. The moisture ratio vs. drying time plot (Figure 2) shows the expected nonlinear relationship for both forced and natural convection drying. We approximated the curves in such plots by two linear segments, representing first and second falling rate

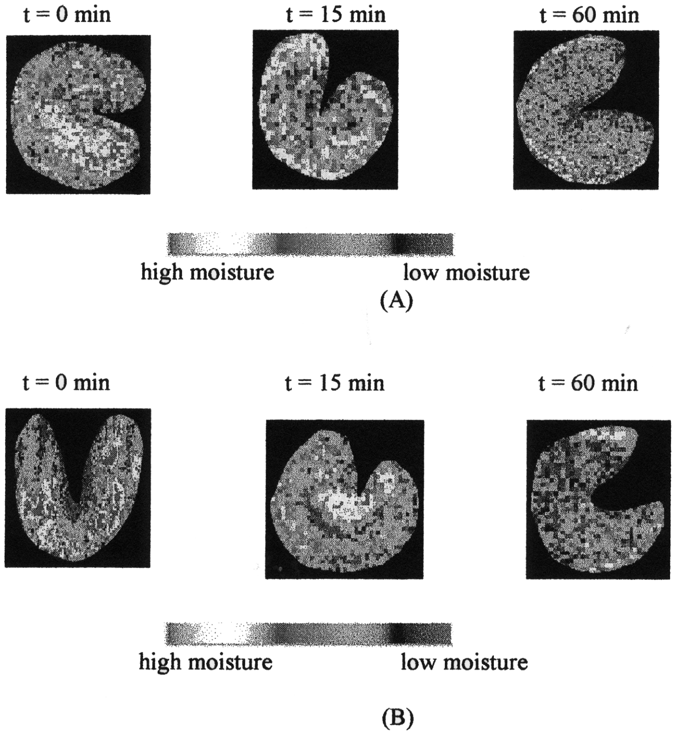


***Figure 1.*** Magnetic resonance images of gelatinized whole wheat grains during drying. (A) Durum wheat, drying temperature = 40°C, (B) Soft wheat, drying temperature = 100°C.

periods (FFRP and SFRP). The bulk mass transfer model we used (equation 5) fitted the data in FFRP and SFRP very well. The transition period (TP) between the two falling rate periods can be characterized by the transition moisture content – the moisture content corresponding to the point of intersection of the two linear segments. This transition moisture content decreased linearly with increasing drying temperature in all experiments as shown in Figure 3. This indicates that at higher temperatures, for both forced and natural convection, most of the drying occurs in FFRP. At all temperatures, the transition moisture content of soft wheat was lower than that of durum wheat.

The internal drying coefficients, $K_{i,1}$ and $K_{i,2}$ were calculated based on equation 5 for FFRP and SFRP, respectively. Both $K_{i,1}$ and $K_{i,2}$ increased linearly with drying temperature (Figures 4 and 5). The $K_{i,1}$ was almost an

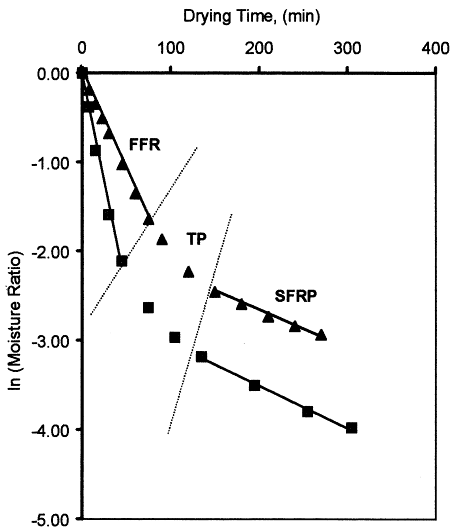


*Figure 2.* First and second falling rate periods (FFRP and SFRP) and transition period (TP) during drying of gelatinized whole wheat grains at 80°C. ■) Forced convection drying, ▲) Natural convection drying.

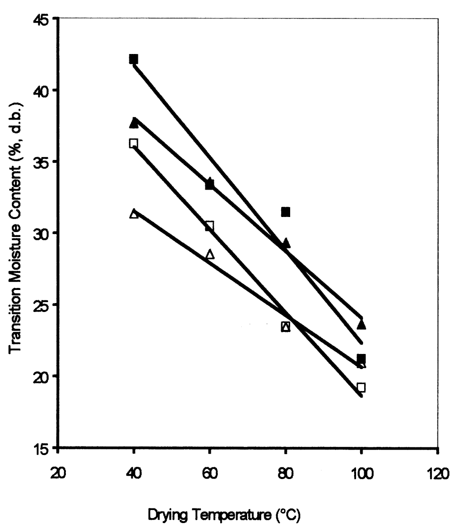


*Figure 3.* Transition moisture content as a function of drying temperature. ■) Durum wheat, forced convection drying; □) Soft wheat, forced convection drying ▲) Durum wheat, natural convection drying; △) Soft wheat, natural convection drying. ($R^2$ of all fits are better than 0.97).

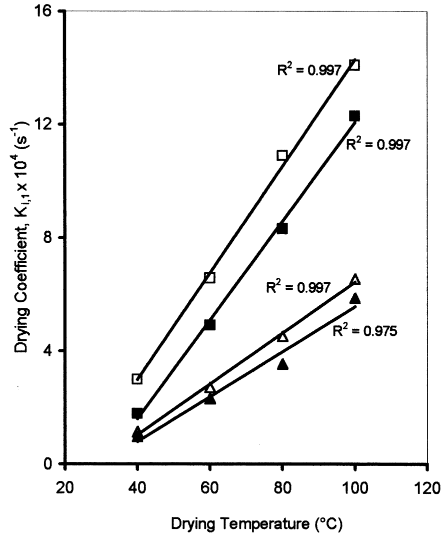


*Figure 4.* Drying coefficient during first falling rate period ($K_{i,1}$). ■) Durum wheat, forced convection drying; □) Soft wheat, forced convention drying; ▲) Durum wheat, natural convection drying; △) Soft wheat, natural convection drying.

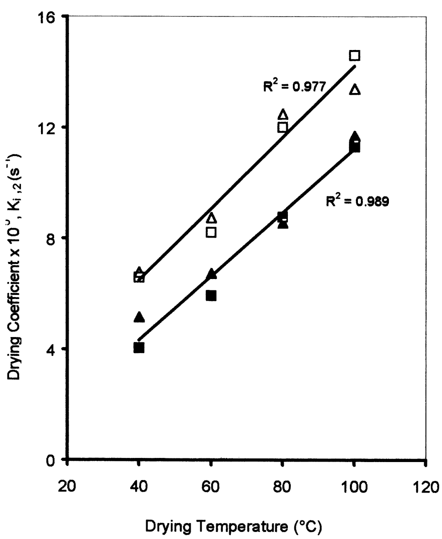


*Figure 5.* Drying coefficient during second falling rate period ($K_{i,2}$). ■) Durum wheat, forced convection drying; □) Soft wheat, forced convention drying; ▲) Durum wheat, natural convection drying; △) Soft wheat, natural convection drying.

order of magnitude higher than $K_{i,2}$. The drying coeffcient was always higher for soft wheat compared to the durum wheat. The magnitude of drying coefficients directly relates to the "resistance" to moisture movement during drying. The differences in composition and microstructure between the durum and soft wheat can be used to explain the observed difference in their resistance to moisture movement. Tightly packed starch granules in the durum wheat are expected to resist moisture movement more so than the relatively less dense granular structure of the soft wheat. Moreover, hard wheat such as durum contains more protein, and has a stronger association between the protein matrix and starch granules than in the soft wheat (Hoseney et al., 1988).

As expected, drying was faster (i.e. larger K values) under forced convection during FFRP where the surface mass transfer rate, which is proportional to air flow rate, is still a contributing factor (Figure 4). In the SFRP, however, the drying mode did not influence the drying coefficients. This is because in the SFRP, the internal resistance to moisture is the sole rate-limiting factor, which is independent of the airflow rate.

The dimensionaless group, $DB_i$ we have proposed continuously decreased with decreasing moisture content at all drying conditions (data not shown). However, $DB_i$ was always greater than 0.1, even at the lowest moisture content we obtained in this study. The magnitude $DB_i$ ($< 0.1$), as in the case of $B_i$, suggests that, in the gelatinized wheat, the resistance to moisture loss at the drying surface is negligible compared to the internal resistance to moisture transfer.

## CONCLUSIONS

The drying of gelatinized soft and durum wheat was in the falling rate period, which can be characterized by two parts – first and second falling rate periods (FFPR and SFRP). A mass balance model was developed to describe the moisture ratio vs. drying time data. The model fitted very well in both FFPR and SFRP. The internal drying coefficients calculated for FFPR and SFRP indicated that drying was faster during FFPR and for soft wheat. The effect of airflow rate was more pronounced during the FFPR than during SFPR.

## REFERENCES

1. Bakshi, A.S. and Sing,-R.P. (1982) Modelling rice parboiling process. Lebensm-Wiss-Technol-Food-Sci-Technol, 15 (2), 89-92.

2. Byler, R.K; Anderson, C.R and Brook, R.C. (1987) Statistical methods in thin layer parboiled rice drying models. Trans. of Am. Soc. Agric. Eng., 30(2), 533-538.
3. Chandra, P.K. and Singh R.P. (1984) Thin-layer drying of parboiled rice at elevated temperature. J. of Food Sci., 49(3), 905-909.
4. Geankoplis, C.J. (1993) Transport Processes and Unit Operations, 3rd ed. Prentice-Hall, Englewood Cliffs, NJ.
5. Hoseney C.R., Wade, P. and Finley, J.W. (1988). Soft wheat prodcucts. In "Wheat Chemistry and Technology, Vol II," Y. Pomeranz (ed.). AACC, St. Paul, MN.
6. Prasad, B.V.S., Chandra, P.K. and Bal, S. (1994) Drying parboiled rough rice in stationary, semi fluidized, and fluidized condtions. Trans. of Am. Soc. Agric. Eng., 37(2), 589-594.
7. Turhan, M. and Gunasekaran, S. (1999). Gelatinization of whole durum wheat during cooking. Abstract No. 37B-18, IFT Annual Meeting Program and Abstracts, Chicago, IL, July 24-28.