MOISTURE DIFFUSIVITY OF LONG-GRAIN RICE COMPONENTS

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ABSTRACT

Moisture adsorption of long-grain rice was modeled using the finite element method. The rough rice kernel was considered a prolate spheroid comprised of three homogeneous components: endosperm, bran, and hull. Adsorption tests were conducted on white, brown, and rough rice of the 'Newbonnet' and 'Lemont' varieties at temperatures ranging from 12° C to 50° C. Diffusivity values were determined for each rice component and each rice form (i.e., rough, brown, and white rice) using a finite element program with an optimization subroutine. White rice had the highest adsorption rate and rough rice the lowest. Endosperm had considerably higher diffusivity values than the bran and hull. The diffusivities of 'Lemont' rice components were found to be more temperature-dependent than those of 'Newbonnet'. The diffusivity temperature-dependency for each rice component and form was described by an Arrhenius-type function.

KEYWORDS. Rice, Moisture, Diffusion.

INTRODUCTION

Rice kernels are hygroscopic materials which adsorb or desorb moisture depending on their ambient environment. Moisture adsorption is a major cause of rice fissuring in the preharvest period and postharvest handling, processing, and storage operations (Kunze, 1977; Srinivas et al., 1978). To better understand the fissuring of rice kernels, the stress/strain distribution within individual kernels during moisture transfer needs to be quantitatively analyzed. This requires information on diffusion behavior of rice kernels exposed to moisture adsorptive or desorptive environments.

It is generally agreed that moisture adsorption or desorption in grains takes place as a simultaneous heat and mass transfer process (Brooker et al., 1974). Diffusion-type equations have been increasingly used to model moisture adsorption or desorption behavior of cereal grains and other farm crops (Whitaker and Young, 1972; Chinnan and Young, 1977; Misra and Young, 1980; Haghighi and Segerlind, 1988; Haghighi et al., 1990; and Laguë and Jenkins, 1991a, b). In modeling moisture diffusion behavior and associated hygroscopic or thermal stresses, material property parameters such as the moisture diffusivity must be known.

Steffe and Singh (1980a, b) determined the diffusivities of short-grain rice during drying using the finite difference method. The rice kernels were assumed to be spheres comprised of three homogeneous components representing the hull, bran, and endosperm. Aguerre et al. (1982) used the diffusion equation to study the drying behavior of medium-grain rough rice. The rough rice kernel was considered as a homogeneous sphere. Engels et al. (1986) employed a similar approach in modeling the water diffusion in long-grain brown and white rice during soaking by assuming rice kernels to be infinite cylinders. Zhang et al. (1984) applied a finite element technique to model the water diffusion in white rice during soaking. The white rice kernel was considered to be a two-dimensional homogeneous body and the diffusivity was assumed to be a function of moisture concentration.

Syarief et al. (1987) determined the diffusivities of corn kernel components during drying using the finite element technique. Muthukumarappan and Gunasekaran (1990) determined the diffusivities of two varieties of corn. Corn kernels were considered as a homogeneous body and three geometries were assumed: the infinite cylinder, infinite slab, and sphere. The diffusivity values determined for the three kernel geometry representations were different.

Most studies have focused on short- or medium-grain rough rice under drying conditions or long-grain white or brown rice during soaking in water. Simple geometries, such as spheres and infinite cylinders were often assumed. Diffusivity data are lacking for long-grain rough rice, especially under moisture adsorptive conditions. Since most rice produced in the United States is the long-grain type, information on the diffusion behavior of long-grain rice is needed. Furthermore, better geometric representation is necessary to accurately model the moisture adsorption or desorption behavior of long-grain rough rice kernels.

OBJECTIVES

The objectives of this study were to:

- Use the finite element technique to model the moisture adsorption behavior of long-grain rough rice.
- Experimentally measure the effects of temperature and relative humidity on the moisture adsorption behavior of rough, brown, and white rice.
- Determine the diffusivities of long-grain rough rice components using the finite element method.

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THEORETICAL CONSIDERATIONS

DIFFUSION EQUATION AND BOUNDARY CONDITIONS

When diffusion in a rice kernel takes place at constant temperature, the moisture diffusion equation alone is sufficient for describing moisture movement. The governing equation for axisymmetric mass transfer in this case is given as follows (Crank, 1975):

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial r^2} + \frac{1}{r}\frac{\partial M}{\partial r} + \frac{\partial^2 M}{\partial z^2}\right) \quad (1)$$

where

- M = moisture concentration [kg/kg (dry basis)]
- D = moisture diffusivity (m^2/h)
- r = radial coordinate (m)
- z = axial coordinate (m)
- t = time variable (h)

In applying equation 1 to a rice kernel, the following assumptions were made: 1) The rice kernel is axisymmetric about its length, kernel thickness and width are equal; 2) the diffusivity is isotropic and independent of moisture concentration; 3) kernel volume change is negligible during moisture transfer. Equation 1 does not include an explicit temperature effect since it is valid only for diffusion under constant temperature conditions. However, the diffusivity value D is known to vary with temperature. The approach used herein to model diffusion at any given level was to determine the diffusivity value as a function of temperature. Hence, the temperature effect on diffusivity is implicitly included in the model.

The following boundary and initial conditions were applied:

$$M = M_e, \text{ at the kernel surface for } t > 0 \quad (2)$$

$$M = M_i, \text{ within the kernel and at the kernel surface for } t = 0 \quad (3)$$

where M_e is the equilibrium moisture content [kg/kg (dry basis)] M_i is the initial moisture content [kg/kg (dry basis)]. The analytical solution to equation 1 is available for simple geometries such as homogeneous spheres, infinite cylinders, and infinite slabs. For problems with irregular boundaries and nonhomogeneous material properties, numerical methods such as the finite element technique must be employed to solve the diffusion equation.

FINITE ELEMENT FORMULATION

The procedure for solving the diffusion equation using the finite element method is well documented (e.g., Segerlind, 1984). The Galerkin's weighted residual integral for equation 1 is:

$$(R) = -\int_V [N]^T\left(\frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial M}{\partial r}\right) + D\,\frac{\partial^2 M}{\partial z^2} - \frac{\partial M}{\partial t}\right) dV \quad (4)$$

in which [N] is a column vector of shape functions. Following the procedure given by Segerlind (1984), the residual integral in equation 4 for an element (e) becomes:

$$\left(R^{(e)}\right) = \left[k^{(e)}\right]\left(M^{(e)}\right) + \left[c^{(e)}\right]\left(\frac{\partial M^{(e)}}{\partial t}\right) = 0 \quad (5)$$

where $[k^{(e)}]$ and $[c^{(e)}]$ are element stiffness and capacitance matrices, respectively. The mathematical expressions for these matrices and for triangular elements can be found in Segerlind (1984). Using the backward difference method and incorporating the known boundary conditions, the final system of equations has the following form:

$$\left([C] + \Delta t[K]\right)(M)_{t+\Delta t} = [C](M)_t + \Delta t\,(F)_{t+\Delta t} \quad (6)$$

in which [K] and [C] are global stiffness and capacitance matrices, respectively, and (F) is a global force vector. Solving equation 6, the nodal moisture content values at time t + Δt are readily obtained given the nodal values at time t.

PROCEDURE

MOISTURE ADSORPTION TESTS

Moisture adsorption tests were conducted on rough, brown, and white rice of two long-grain varieties, 'Lemont' and 'Newbonnet'. The rice samples were obtained from the University of Arkansas Northeast Research and Extension Center at Keiser, Arkansas. The brown rice was obtained by hand shelling rough rice so as to minimize damage to the bran layers. White rice (endosperm) samples were obtained by first shelling rough rice using a McGill huller. The amount of rough rice for each milling sample was 150 g. The resulting brown rice was then milled using a McGill No. 2 mill for 30 s with a 1.5 kg weight on the lever arm 150 mm from the center of the milling chamber. Whole rice kernels were separated from brokens using a Seedboro sizing machine. Prior to testing, the thickness, width, and length dimensions of 100 kernels of rough, brown, and white rice were measured using a micrometer to within 0.01 mm (Table 1).

Adsorption tests were conducted in a conditioning chamber with air supplied by a Parameter Generation and Control 300 CFM Climate Lab-AA temperature and relative humidity control unit. This unit is capable of maintaining relative humidity within ± 0.5% and dry-bulb temperature within ± 0.2°C. Eight moisture adsorption tests were performed. Five tests were conducted at temperatures of 12.0, 20.0, 30.2, 40.3, and 50.2° C with relative humidity ranging between 84 and 90%. The three remaining tests were conducted at temperatures of 15.0, 25.0, and 35.1° C with a relative humidity of approximately 75%. The initial moisture contents of 'Lemont' and 'Newbonnet' rice are presented in Table 2.

Samples, each of 200 kernels, were placed in wire-mesh baskets. The length, width, and height dimensions of each basket were approximately 7.0 × 7.0 × 1.5 cm, respectively. The baskets were sufficiently large so that there was little kernel-to-kernel contact. Each 200-kernel sample was weighed to an accuracy of ± 0.1 mg using an

TABLE 1. Kernel dimensions (mm) and dry matter weights (mg)

	'Newbonnet'			'Lemont'		
	Rough	Brown	White	Rough	Brown	White
Thickness						
Mean*	1.81	1.65	1.60	1.91	1.71	1.63
S.D.†	0.07	0.06	0.07	0.06	0.06	0.05
Width						
Mean*	2.27	2.08	2.03	2.56	2.31	2.24
S.D.	0.14	0.11	0.12	0.12	0.08	0.09
Length						
Mean*	8.89	6.89	6.72	9.06	6.87	6.70
S.D.	0.51	0.32	0.34	0.52	0.46	0.41
Weight						
Mean‡	19.5	16.1	14.6	22.9	18.5	16.8
S.D.	0.4	0.1	0.3	0.5	0.4	0.3

* Mean of 100 measurements.
† Standard deviation.
‡ Mean kernel dry matter weight from 32,200-kernel samples.

analytical balance (Fisher Scientific 200-DA). Samples were then placed in the conditioning chamber. At specified times, samples were removed from the chamber for weight measurements. The test duration was 72 h for temperatures below 25° C and 48 h for temperatures above 25° C. Such time periods allowed the white and brown rice to reach the equilibrium moisture content and rough rice to approach the equilibrium moisture content. The moisture contents of rice samples were determined by oven drying for 24 h at a temperature of 130° C. All the experiments were replicated.

TABLE 2. Initial (first line of pair) and equilibrium (second line of pair) moisture contents (%, d.b.) of 'Newbonnet' and 'Lemont' rough, brown, and white rice*

		'Newbonnet'			'Lemont'		
Temp. (° C)	RH (%)	Rough	Brown	White	Rough	Brown	White
12.0	83.5	12.08	13.11	13.03	12.55	13.45	13.43
		20.85	21.53	21.60	20.74	21.71	21.92
20.0	90.3	12.19	12.99	13.15	12.53	13.42	13.27
		23.36	24.27	24.14	23.59	24.44	24.06
30.2	87.4	12.22	13.32	13.37	12.61	13.74	13.59
		21.60	22.99	22.82	21.75	23.13	22.83
40.3	85.9	12.06	13.18	13.08	12.41	13.46	13.40
		21.34	22.66	22.26	21.11	22.44	22.05
50.2	86.5	12.26	13.22	12.96	12.63	13.59	13.38
		22.61	23.31	21.99	21.26	22.34	21.56
15.0	74.5	12.07	13.13	13.00	12.61	13.52	13.46
		17.63	18.75	18.81	17.98	19.04	19.11
25.0	75.1	11.89	13.01	13.04	12.43	13.45	13.54
		17.56	18.77	18.88	17.88	18.95	19.11
35.1	75.3	12.08	13.17	13.10	12.54	13.49	13.41
		17.24	18.52	18.48	17.35	18.55	18.48

* Each value in the table is the average of two measurements determined from oven drying.

FINITE ELEMENT MODELING

A computer program for two-dimensional, steady-state field problems written by Segerlind (1984) was modified to solve time-dependent axisymmetric diffusion problems. A subroutine based on the Golden Section search method (Jacoby et al., 1972) was written to evaluate the diffusivities of 'Lemont' and 'Newbonnet' rough rice. The modified computer program was used to determine the diffusivity and to evaluate the average kernel moisture content and moisture distributions within the kernel. The average kernel moisture content was computed using the mass average method (Haghighi and Segerlind, 1988)

$$\overline{M}(t) = \frac{\int_v M(r, z, t)\, dm}{\int_v dm} \quad (7)$$

where dm is an element of mass and $\overline{M}(t)$ is mass average kernel moisture content at time t, kg/kg (dry basis).

Kernel Geometry. In this study, the rice kernel shape was assumed to be a prolate spheroid, which is formed when an ellipse is rotated about its major axis. Laguë and Jenkins (1991a, b) also considered the medium-grain rice kernel as a prolate spheroid. The dimension of the minor axis for the prolate spheroid was taken as the average of the measured kernel thicknesses and widths, and the dimension of the major axis was equal to the mean of the measured kernel lengths. Table 1 summarizes the kernel dimensions measured from 100 kernels each of rough, brown, and white rice for the 'Lemont' and 'Newbonnet' varieties. The table also shows individual rice kernel dry matter weights based on 32,200-kernel sample weight measurements for each rice form (i.e., rough, brown, and white rice).

Figure 1 shows an idealized rough rice kernel comprised of three homogeneous components representing the hull, bran, and endosperm. The ratios of hull, bran, and endosperm volume to the whole rough rice kernel volume for the 'Newbonnet' idealized rice kernel were 0.348, 0.050, and 0.602, respectively. The ratios of hull, bran, and endosperm volume to the whole rough rice kernel volume for the 'Lemont' rice kernel were 0.386, 0.056, and 0.558, respectively. Based on the dimensions of the idealized kernel and the average kernel dry matter weight of each

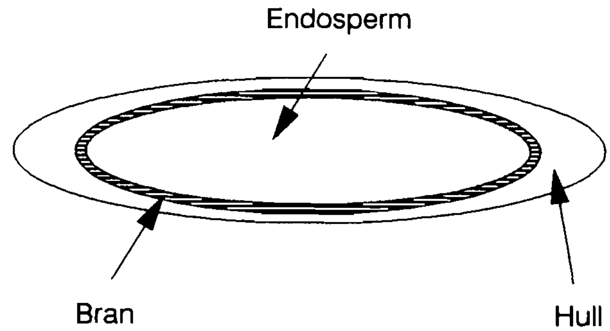

Figure 1–An idealized long-grain rough rice kernel.

rice form, the kernel densities of the 'Newbonnet' rough, brown, and white rice at a moisture content of 13.0% were found to be 1137, 1444, and 1420 kg/m^3, respectively (all moisture contents reported herein are on a dry basis). The kernel densities of the idealized 'Lemont' rough, brown, and white rice were 1093, 1441, and 1440 kg/m^3, respectively. These density values are in close agreement with the data presented in ASAE standards (ASAE, 1990) for rough rice kernels and by Bhattacharya et al. (1972) and Yamaguchi et al. (1977) for brown and white rice kernels. The densities for 'Newbonnet' hull and bran were found to be 562 and 1736 kg/m^3, respectively. The densities for 'Lemont' hull and bran were 538 and 1453 kg/m^3, respectively.

Finite Element Grid. The idealized rice kernel was discretized into linear triangular elements as shown in figure 2. The grid for the rough rice kernel consisted of 108 nodes and 172 elements, of which 100 elements were used for the endosperm, 27 elements for the bran, and 45 elements for the hull.

The procedure, which used the finite element method for evaluating the diffusivities of endosperm, bran, and hull, was similar to that described by Steffe and Singh (1980a). The diffusivity of the endosperm at a specified air temperature and relative humidity was first evaluated. For each run of the finite element program, the sum of squared deviations between the measured and finite element-predicted moisture contents was calculated. The diffusivity value was adjusted in successive iterations using the Golden Section search method (Jacoby et al., 1972). The diffusivity of the endosperm was obtained when the sum of squared deviations between the measured and predicted moisture contents was minimum. The diffusivity of the bran was then determined from the brown rice adsorption data using the known diffusivity value for endosperm. Finally, the diffusivity of the hull was determined from the rough rice adsorption data using the known diffusivity values for endosperm and bran. In addition, the diffusivity values were also determined for brown and rough rice kernels when each rice form was considered as a single, homogeneous material. The time step used in the finite element computations was 0.1 h.

Results and Discussion

Moisture Adsorption Tests

Figure 3 shows one set of moisture adsorption data for 'Newbonnet' rough, brown, and white rice with an initial moisture content of about 13% at an air condition of 30.2° C and 87.4% relative humidity. White rice had the

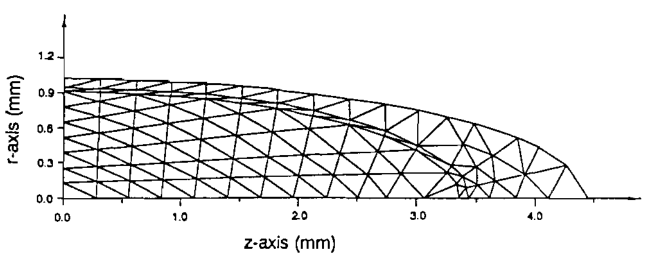

Figure 2–Finite element grid for an axisymmetric model of a long-grain rough rice kernel (108 nodes, 172 elements).

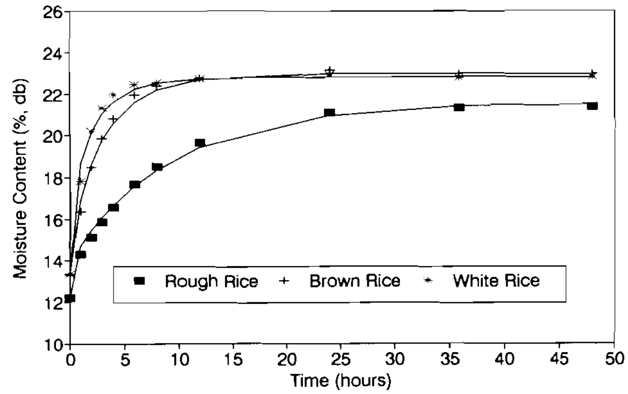

Figure 3–Experimentally determined moisture contents (symbols) along with finite element predictions (solid lines) of moisture content of 'Newbonnet' rough, brown, and white rice at 30.2° C and 87.4% relative humidity.

highest adsorption rate and the rough rice the lowest. White and brown rice reached equilibrium within 24 h for all the test conditions. Therefore, the final moisture contents of white and brown rice were taken as equilibrium moisture contents. However, after 72 h of exposure to the conditioned air at temperatures below 25° C, rough rice still had not reached equilibrium. In order to obtain the equilibrium moisture contents for the rough rice, the experimental adsorption data were fitted to the following equation

$$M(t) = M_e + (M_i - M_e)\exp(-k t^n) \tag{8}$$

in which k and n are constants. This equation was chosen based on numerous reported modeling studies of drying and rewetting characteristics of rice and other cereal grains (e.g., Banaszek and Siebenmorgen, 1990). The NLIN procedure (SAS, 1988) was used to fit equation 8 to each adsorption curve. The M_e value determined from the NLIN procedure was considered as the equilibrium moisture content for rough rice and was used in the finite element model. The differences between the equilibrium moisture content and measured final moisture content of 'Newbonnet' and 'Lemont' rice were less than 0.6 percentage points for all adsorption tests with the exception of the 12.0° C test for which the difference was about 1.4 percentage points.

The experimental results in Table 2 indicate that brown rice had approximately the same equilibrium moisture content as white rice and rough rice had a lower equilibrium moisture content under all test conditions. With the exception of 12° C, the equilibrium moisture contents of 'Lemont' rough, brown, and white rice were higher than those of 'Newbonnet' when the temperature was below 35° C. However, the differences were within 0.3 percentage points. At temperatures of 40 and 50° C, 'Newbonnet' white, brown, and rough rice showed higher equilibrium moisture contents than 'Lemont' white, brown, and rough rice with the differences ranging from 0.2 to 1.4 percentage points. These results indicate that the responses of rice kernels to temperature were not exactly the same for the 'Lemont' and 'Newbonnet' varieties.

Diffusivity Determination

Figure 3 shows that predicted moisture contents compared well with the experimental data at 30.2° C. Average absolute differences were 0.29, 0.24, and 0.21 percentage points for the white, brown, and rough rice, respectively. Similar results were also obtained for other test conditions. Table 3 summarizes the diffusivity values for each rice component and the means of the squared deviations between measured and finite element-predicted moisture contents for the 'Newbonnet' and 'Lemont' varieties. The low values of the mean of the squared deviations indicate that the finite element model performed well in modeling moisture adsorption of long-grain rough rice. The diffusivities of endosperm were considerably higher than those of the bran and hull (Table 3). The hull had the lowest diffusivity values, which indicates that the hull was more resistant to moisture transfer than the endosperm and bran. The diffusivities of endosperm, bran, and hull increased with temperature. The diffusivities of the 'Lemont' endosperm were higher than those of the 'Newbonnet' endosperm, yet the difference was always less than 5%. The diffusivities of the hull were considerably higher (ranging from 7 to 28%) for the 'Lemont' variety than for the 'Newbonnet' variety. When the temperature was below 20° C, 'Newbonnet' bran had a higher diffusivity than 'Lemont' bran. However, as temperature increased, the diffusivity of the 'Lemont' bran increased more rapidly than the diffusivity of the 'Newbonnet' bran. The presence of higher diffusivities for the hull and bran of the 'Lemont' variety implies that moisture can be transferred through the hull and bran faster. Thus greater moisture gradients can occur in the 'Lemont' endosperm, which in turn can induce greater stresses. This may partly explain why 'Lemont' rice has been reported to be more susceptible to fissuring due to moisture adsorption than 'Newbonnet' rice (Lan and Kunze, 1990).

Table 4 shows the diffusivities of the brown and rough rice for both 'Newbonnet' and 'Lemont' varieties when each was considered as a single, homogeneous material. For the same test conditions, the means of squared deviations for brown and rough rice are considerably higher than those for the endosperm, bran, and hull (Table 3). This indicates that the rough rice kernel was better modeled as a composite body rather than a single, homogeneous body. When the temperature was below 40° C, 'Newbonnet' brown rice had a higher diffusivity value than 'Lemont' brown rice; at temperatures of 40 and 50° C, 'Lemont' brown rice had a higher diffusivity value. 'Lemont' rough rice had a higher diffusivity value than 'Newbonnet' rough rice under all test conditions. This is explained by the higher diffusivity of the hull for the 'Lemont' variety as compared to the 'Newbonnet' variety, as is shown in Table 3.

The diffusivity temperature-dependency of each rice component and form was fitted to the Arrhenius-type function used by Steffe and Singh (1980a, b):

$$D = A \exp\left(-\frac{B}{T_a}\right) \quad (9)$$

TABLE 3. Diffusivity values for 'Newbonnet' and 'Lemont' endosperm, bran, and hull (× 10^8, m^2/h)*

Temp. (° C)	RH (%)	'Newbonnet' Endosperm	'Newbonnet' Bran	'Newbonnet' Hull	'Lemont' Endosperm	'Lemont' Bran	'Lemont' Hull
12.0	83.5	1.503	0.210	0.157	1.550	0.205	0.210
		(2.329)	(0.599)	(0.703)	(2.224)	(0.512)	(1.022)
20.0	90.3	3.384	0.448	0.339	3.500	0.454	0.379
		(2.149)	(0.867)	0.905)	(2.178)	(0.779)	(1.524)
30.2	87.4	4.905	0.804	0.690	5.039	0.903	0.833
		(0.848)	(0.578)	(0.432)	(0.920)	(0.583)	(0.617)
40.3	85.9	8.363	1.700	1.237	9.075	1.947	1.492
		(0.223)	(0.886)	(0.191)	(0.265)	(0.161)	(0.257)
50.2	86.5	11.156	2.546	1.702	11.690	3.980	2.366
		(0.508)	(0.298)	(0.593)	(0.255)	(0.394)	(0.309)
15.0	74.5	1.205	0.303	0.226	1.217	0.274	0.276
		(1.026)	(0.488)	(0.123)	(0.986)	(0.432)	(0.244)
25.0	75.1	2.614	0.508	0.487	2.671	0.567	0.522
		(0.508)	(0.247)	(0.143)	(0.477)	(0.257)	(0.219)
35.1	75.3	4.689	1.156	0.990	4.741	1.306	1.205
		(0.172)	(0.134)	(0.088)	(0.128)	(0.135)	(0.097)

* The values in parentheses are the means of squared deviations between measured and finite element-predicted moisture contents [× 10^5, $(kg / kg)^2$].

TABLE 4. Diffusivity values for 'Newbonnet' and 'Lemont' brown and rough rice when each was modeled as a single, homogeneous material (× 10^8, m^2/h)*

Temp. (° C)	RH (%)	'Newbonnet' Brown	'Newbonnet' Rough	'Lemont' Brown	'Lemont' Rough
12.0	83.5	0.697	0.250	0.607	0.294
		(3.864)	(1.546)	(4.278)	(1.637)
20.0	90.3	1.645	0.552	1.436	0.564
		(4.700)	(2.447)	(5.160)	(2.645)
30.2	87.4	2.846	1.105	2.719	1.173
		(2.323)	(1.509)	(2.531)	(1.330)
40.3	85.9	5.568	2.007	5.616	2.200
		(1.342)	(0.837)	(0.693)	(0.757)
50.2	86.5	7.703	2.787	8.976	3.517
		(1.123)	(1.077)	(0.926)	(0.644)
15.0	74.5	0.725	0.351	0.695	0.381
		(1.502)	(0.425)	(1.703)	(0.508)
25.0	75.1	1.568	0.719	1.492	0.731
		(0.995)	(0.362)	(1.042)	(0.384)
35.1	75.3	3.311	1.533	3.236	1.622
		(0.418)	(0.278)	(0.434)	(0.242)

* The values in parentheses are the means of squared deviations between measured and finite element-predicted moisture contents [× 10^5, $(kg / kg)^2$].

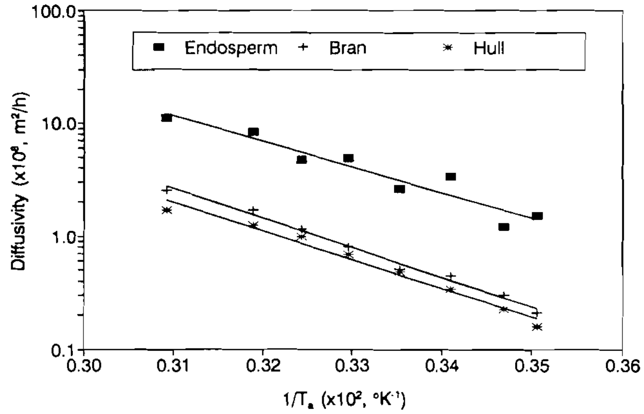

Figure 4–Relationships between diffusivity and temperature for 'Newbonnet' rough rice components.

where D has the units of m^2/h, A and B are constants, and T_a is the absolute temperature.

Using the least-square regression technique, the Arrhenius-type models were found for each rice component and each rice form. Figures 4 and 5 show the diffusivities of 'Newbonnet' rice at various temperatures along with regression lines for a least square fit to the Ln (natural log) transformation of equation 9. In all cases, the regression equations fit the diffusivity data very well. Table 5 summarizes the values of the coefficients A and B and the corresponding R^2 values for each rice component and form for both the 'Newbonnet' and 'Lemont' varieties. In view of the high R^2 values, the temperature-dependency of diffusivity was satisfactorily described by the Arrhenius-type function.

The diffusivity of the brown rice obtained in this study is comparable to that given by Yamaguchi et al. (1982) with a difference of about three percent points. However, the diffusivity values obtained in this study for the hull, bran, and endosperm are significantly lower than those reported by Steffe and Singh (1980a). The relative differences range from 100 to 400%. Such large differences are likely to be attributed to the following factors: 1) varietal or grain type difference. The rice used by Steffe and Singh was a short-grain variety; 2) different

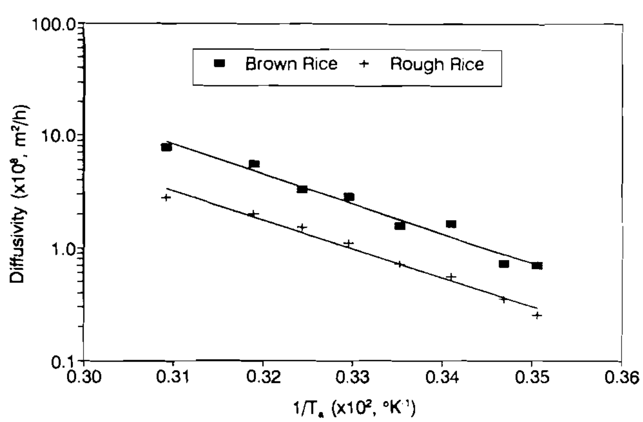

Figure 5–Relationships between diffusivity and temperature for 'Newbonnet' brown and rough rice.

TABLE 5. The coefficients A and B in equation 9 and the corresponding R^2 values

Rice Form	A	B	R^2
		'Newbonnet'	
Endosperm	1.1855	5206.1	0.911
Bran	3.2867	6013.5	0.990
Hull	1.4641	5842.8	0.978
Brown rice	12.8355	6080.8	0.967
Rough Rice	2.968	5917.4	0.983
		'Lemont'	
Endosperm	1.6163	5289.5	0.906
Bran	110.9690	7042.5	0.997
Hull	3.0101	6000.5	0.993
Brown rice	79.2446	6639.4	0.983
Rough rice	5.9835	6101.4	0.996

test conditions, i.e., adsorption versus desorption; and 3) different geometry assumptions for rice kernels. Steffe and Singh considered the rough rice kernel to be a composite sphere. Muthukumarappan and Gunasekaran (1990) compared the diffusivities of corn kernels for three different geometry representations. They found that the diffusivity values of corn kernels using the infinite slab geometry were about one to 2.5 times the diffusivity values using the infinite cylinder geometry.

Conclusions

1. Moisture adsorption of 'Newbonnet' and 'Lemont' long-grain rice was satisfactorily simulated by the finite element model which assumed the kernel shape to be a prolate spheroid.
2. The equilibrium moisture contents of white and brown rice were higher than those of rough rice for all test conditions. White rice had the highest moisture adsorption rate, and rough rice had the lowest adsorption rate. White and brown rice reached equilibrium moisture content within 24 h.
3. The endosperm had considerably higher diffusivity values than the bran and hull. The hull had the lowest diffusivity values and, therefore, was more resistant to moisture transfer. The diffusivities of the endosperm, bran, and hull increased with temperature. The temperature-dependency of the diffusivity of each rice component and form was well described by an Arrhenius-type function.

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