MOISTURE ADSORPTION CHARACTERISTICS OF WHEAT AND BARLEY

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ABSTRACT. *Moisture adsorption rates for stored grains are important for accurate modeling of drying and storage. Wheat and barley samples at initial moisture contents typical of grain storage were exposed to several levels of higher humidity at two temperatures to measure adsorption rates. The best fit to the data was achieved with the Page equation and the cellular diffusion equations. The adsorption rates were lower than those of comparable desorption tests. The adsorption rates for barley were lower than for wheat due to lower diffusion coefficients for the barley endosperm and germ as compared to wheat.*

Keywords. *Grain storage, Modeling, Diffusion, Desorption, Thin–layer, Grain drying.*

After harvest and cleaning, agricultural products are generally at the highest possible quality level. About one–half of the world's cereal grain production goes into storage after harvest, where significant quality loss may occur (White, 1995). Computer simulations of grain storage have been developed in recent years as an aid to improve grain storage and reduce storage losses (Jayas, 1995). However, simulating the storage of grain is hampered due to insufficient data in the literature to predict rates of adsorption of moisture by wheat and barley during storage.

Considerable data are available on rates of moisture desorption from grain during drying. Studies on storage of grain and grain–type products have often had to rely on these moisture desorption data for describing moisture transfer, even though moisture transfer during storage involves both moisture desorption and moisture adsorption in the grain. In a storage bin that is not aerated or ventilated, any moisture movement must involve one–half desorption and one–half adsorption to maintain conservation of mass. If adsorption of moisture by grain kernels occurs at different rates than desorption, using desorption data alone in grain storage models may impair the accuracy of predictions.

A few studies in the literature provided data on moisture adsorption rates for selected materials, especially corn (e.g., Muthukumarappan and Gunasekaran, 1990) and rice (e.g., Lan and Kunze, 1996). A literature review revealed no data sufficient for modeling moisture adsorption rates of wheat and barley over a range of storage conditions. Aldis and Foster (1980), Duggal et al. (1982), and Versavel and Muir (1988) presented some moisture adsorption information for wheat kernels and spikes, but did not give the needed adsorption rates for kernels. Babbitt (1949) gave some qualitative information about moisture adsorption by wheat kernels, but only determined constants for the spherical diffusion equation, with negligible external resistance, for one condition (25°C, 75% relative humidity).

The desorption of moisture from grain kernels during drying nearly always occurs in the falling–rate drying period in which there is no free moisture. Moisture adsorption is the reverse of this process; however, because of differences between adsorption by cells in the product as compared to desorption, adsorption may occur at different rates. The theory of falling–rate desorption has been thoroughly developed (e.g., Henry, 1939; Henry, 1948; Luikov, 1966). The resulting two coupled partial differential equations describing heat and moisture diffusion may generally be uncoupled due to the different rate of heat transfer as compared to mass transfer during drying (see Parti, 1993), leading to thin–layer drying equations referred to herein as diffusion equations.

There have also been many empirical equations developed, because they often have as good or greater accuracy in a specific application with less computational effort than the theoretical equations. The exponential drying equation (Lewis, 1921; Sherwood, 1936) has been useful in some cases for describing thin–layer drying; however, it gives a poor description of the initial part of the drying process (Hukill and Schmidt, 1960). It is possible that the exponential drying equation will be more accurate for grain storage, because there is more boundary layer resistance than with drying due to the slow–moving or even stagnant air in storage situations. Page (1949) developed an empirical equation that has proven to be considerably more accurate than the exponential drying equation. After many years of widespread use, the Page equation is now often accepted as the preferred equation for drying work (*ASAE Standards*, 1994b).

The diffusion equations have usually been based on the simplifying assumption that grain kernels are homogeneous. Walton and Casada (1986) developed cellular diffusion–based equations based on the actual nonhomogeneous

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internal cell structure of foliar material. These models account for different resistances to moisture diffusion within the biological material by allowing finite resistance to moisture at the surface. One cellular diffusion–based drying model was applied to a wide range of drying data for shelled corn by Walton et al. (1988) and found to fit the data better than the Page equation. Osborn et al. (1991) applied this model to a limited number of cases for moisture adsorption in soybeans and found that the Page equation fit their data slightly better than this cellular diffusion model.

As mentioned, the literature does not contain data on moisture adsorption for wheat and barley beyond one data point for wheat at one temperature and relative humidity. Because of this lack of moisture adsorption data, the objectives of this research were to:

1. Determine the thin–layer moisture adsorption rates of wheat and barley kernels under grain storage conditions.
2. Determine the most appropriate equations to describe this moisture adsorption in wheat and barley kernels.

Candidate Thin–Layer Models

Six equations from the literature were selected for evaluation as candidates for describing the moisture adsorption characteristics of wheat and barley kernels. (Please see definitions of terms in the Nomenclature section.)

The exponential drying equation (the diffusion equation with zero internal resistance) (Sherwood, 1936):

$$\overline{MR} = \exp[-k \cdot t] \tag{1}$$

The Page equation (Page, 1949):

$$\overline{MR} = \exp[-K \cdot t^n] \tag{2}$$

The spherical diffusion equation with finite surface resistance (Crank, 1975; Walton and Casada, 1986):

$$\overline{MR} = 6 \sum_{n=1}^{\infty} A_n \exp[-(D'/R^2)(\lambda_n R)^2 t] \tag{3a}$$

where $\lambda_n R$ are solutions of:

$$\lambda_n R \cdot \cos(\lambda_n R) = (1 - Bi_m) \cdot \sin(\lambda_n R) \tag{3b}$$

The cylindrical diffusion equation with finite surface resistance (Crank, 1975; Walton and Casada, 1986):

$$\overline{MR} = 4 \sum_{n=1}^{\infty} B_n \exp[-(D'/R^2)(\lambda_n R)^2 t] \tag{4a}$$

where $\lambda_n R$ are solutions of:

$$\lambda_n R \cdot J_1(\lambda_n R) = Bi_m \cdot J_0(\lambda_n R) \tag{4b}$$

The spherical diffusion equation with zero surface resistance (Crank, 1975):

$$\overline{MR} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp[-(D'/R^2) \cdot n^2 \cdot \pi^2 \cdot t] \tag{5}$$

The cylindrical diffusion equation with zero surface resistance (Crank, 1975):

$$\overline{MR} = 4 \sum_{n=1}^{\infty} \frac{1}{(\lambda_n R)^2} \exp[-(D'/R^2)(\lambda_n R)^2 t] \tag{6a}$$

where $\lambda_n R$ are solutions of:

$$J_0(\lambda_n R) = 0 \tag{6b}$$

In the cellular–based finite surface resistance diffusion models, the two parameters determined from experiment are the diffusion coefficient (D') and the modified Biot number for mass transfer (Bi_m). The parameter D' is essentially the inverse of internal resistance, and Bi_m is the ratio of internal to external resistance. These finite surface resistance models are distinctly different from other models commonly used in grain drying, because they model diffusion out of the internal tissue, endosperm and germ, and consider the surrounding tissue, the bran (plus the husk if present), to be external resistance. The modified Biot number includes the resistance of the bran and husk and the resistance to convective mass transfer at the surface.

The zero surface resistance diffusion equations contain only one parameter, D', because they are based on the assumption of only one component of resistance to diffusion (internal) in homogeneous particles. Thus, Bi_m is assumed to be infinite and is not a parameter to be determined. The neglected external resistance is assumed to be only the convective resistance, which does not include cellular resistance such as the bran layers. This assumption is accepted in drying situations, because the convective resistance is typically negligible in comparison to the internal resistance, but it is not accurate when the resistance of the bran and husk are included (Walton et al., 1988). These zero surface resistance diffusion equations cannot account for resistance to moisture that may exist at the surface due to the moderate Biot numbers in grain storage situations and, more importantly, they cannot account for the nonhomogeneity of the internal cell structure.

Materials and Methods

Wheat and barley kernels were subjected to adsorption at three levels of relative humidity and at two temperature levels, which are shown in table 1. Tests were replicated three times, with the exception of barley at 15°C and 58% relative humidity, where there was only one test due to an error that destroyed two samples. Selected desorption conditions and varying airflow rates were also tested for comparison. Saturated salt solutions were used to maintain a constant relative humidity environment for the tests. ASAE standard thin–layer drying procedures (*ASAE Standards*, 1994b) were generally followed except for the air velocity. A lower air velocity, 0.16 m/s (typical of grain storage bins), was used for all tests except when the influence of air velocity was being studied. In these cases, still air or a velocity of 0.32 m/s was used for comparison to 0.16 m/s. Typical relative humidities in aerated storage bins containing dry grain are between 35% and 55%, and typical temperatures are near 15°C; however, the higher levels of relative humidity and temperature occur when problem areas develop in grain storage bins. The higher relative humidities also occur during aeration with moist air. The higher temperatures also exist frequently in non–aerated storage bins.

Table 1. Test conditions for thin–layer adsorption tests.

Relative Humidity	Grain Type Tested	
	15°C	30°C
50%	—	barley, wheat
58%	barley, wheat	—
71%	—	barley, wheat
78%	barley[a], wheat[a]	barley[a], wheat[a]
85%	barley[b], wheat[b]	—

[a] Comparison desorption tests also run.
[b] Comparison high and zero airflow tests also run.

Both wheat and barley samples were harvested from the 1993 crop at typical moisture contents and were stored in moisture proof containers at a temperature of 5°C. The samples were cleaned using a small fanning mill and again stored in moisture proof containers. Storage times before testing ranged from 14 to 28 months. Initial adsorption test moisture contents were essentially unchanged from harvest and were 10.5% ±0.2% dry basis for barley and 11.4% ±0.5% dry basis for wheat.

Test samples were suspended from load cells in a sealed test cubicle that contained saturated salt solutions to maintain the desired relative humidity. Test samples were placed one kernel deep on 25 cm × 25 cm wire screen baskets. Three baskets at a time were placed inside the test cubicle, giving three replications. The 70 cm × 90 cm × 60 cm high test cubicle was constructed of Plexiglas and plywood. The plywood was sealed with three coats of marine varnish. The top of the test cubicle was fitted with three load cells (Omega Engineering, Inc., Model LCL–227G) to regularly monitor sample weight during the tests. The load cell outputs were measured through an analog–to–digital board (Computer Boards, Model CIO–DAS08) in a personal computer using commercial data acquisition software. This program also controlled the operation of the fans through a relay, turning them off for two minutes every half–hour to obtain weight readings that were unaffected by the air flow.

For the still air tests, a rack was placed at approximately the mid–height of the cubicle to hold the salt solution trays at a height near the sample. For the moving air tests, the rack was removed, the salt trays were placed in the bottom of the cubicle, and fans between the trays and the sample baskets were used to maintain a constant velocity upward through the test sample. Several layers of screens were used between the fan and sample to provide uniform velocity through the samples. A hot wire anemometer was used to confirm the uniformity.

Groups of samples at the same initial moisture content and grain type were first selected, weighed, and placed in the wire screen sample holders. Samples in the holders were stored in moisture–proof containers, brought to the desired test temperature in an environmental chamber, and allowed to equilibrate for at least 24 hours prior to each test. The test cubicle was located in this same constant–temperature environmental chamber. Each sample was then placed in the test cubicle and allowed to come to equilibrium, or near equilibrium, with the humidity maintained by the salt solution. The average standard deviation for the test temperatures in the test cubicle was 0.4°C. For relative humidity, the standard deviation was 0.6 percentage points. Sample weights were monitored until the weight ceased to change, or until MR was less than 0.05 in cases where the test was terminated before complete equilibrium was achieved. After completion of the testing for each sample, the entire test sample was oven dried according to ASAE time and temperature standards (*ASAE Standards*, 1994a) to determine its actual dry weight for calculating moisture contents during the tests.

The fan screens were adjusted to give a uniform airflow rate of 0.32 m/s at full flow. The lower rate, 0.16 m/s, was obtained by restricting the fan inlets. The load cells were calibrated, with the sample baskets in place as the zero point, over the range of sample weights using a precision weight set. The constant voltage supply of 9.75 V for the three load cells was provided by a 12 V automotive battery with a voltage divider circuit.

The parameters for the drying equations were determined for each data set using the NLIN least squares best fit procedure of SAS (SAS, 1987). The data for MR from 1.0 to 0.1 were fit to the model equations when determining these parameters. For the series equations, the first 40 terms were used in the fit. The equilibrium moisture content in each case was determined by first fitting the Page equation to the entire data set (i.e., $MR_{final} \leq 0.05$). For equations where Bi_m was a parameter to be determined, the eigenvalues were first calculated for discrete values of Bi_m from 0.2 to infinity, and NLIN was used to fit the equation for the different values of Bi_m. The increment of tested Bi_m was 1.0 for values from 1.0 through 10.0, and the increment was gradually increased for values of Bi_m greater than 10.0. The case of Bi_m with the lowest standard error of regression was selected as the best fit standard error, while the value of Bi_m was interpolated between the closest increments. With these increments, only a slight improvement in standard error could have been achieved with additional intermediate values of Bi_m.

Results and Discussion

Plots of moisture ratio (MR) results from one adsorption test are shown in figure 1. In this case, as with most wheat tests, the Page equation could not be distinguished from the cellular–based finite surface resistance diffusion equations in the plot. The exponential drying equation did not fit the data nearly as well as the Page and finite surface resistance equations, as indicated by the standard errors of regression, although the shape of the curve was not dramatically different from the data for the particular case shown (with a relatively low Biot number, Bi_m = 3.0). The goodness of fit for all candidate equations was evaluated with the standard error of regression. Tables 2 and 3 show the average standard errors of regression for three replications at each condition for the wheat and barley tests, respectively.

Overall, the Page equation and either of the cellular–based finite surface resistance diffusion equations described the data better than the other tested equations, based on the standard errors of regression. These three equations were essentially equal in their ability to fit the adsorption data well. The overall average standard error of regression, averaged over all basic adsorption tests, was 0. 0.0103 for both the Page equation and the spherical finite surface resistance diffusion equation, and was 0.0102 for the cylindrical finite surface resistance diffusion equation (units of MR). Not only are the average standard errors nearly equal, but the individual tests also exhibited little difference between goodness of fit for

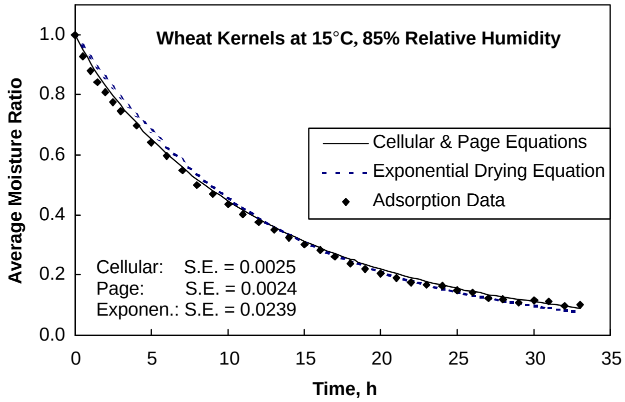

Figure 1. Comparison of observed and predicted average moisture ratio using the Page equation and the cellular–based finite surface resistance diffusion equation.

these three models. While these models are equal in accuracy, the Page equation is generally preferable for modeling work because of its simplicity for computation. The finite surface resistance diffusion equations are more useful for studying details of moisture movement in the grain kernels. Parameters for the Page equation are given in table 4.

In previous work with corn desorption (Walton et al., 1988), the cellular–based finite surface resistance diffusion equation was found to fit better than the Page equation in 19 of 20 conditions tested. The Page equation fit better in one of four tests at the lowest temperature tested (38°C). With adsorption in soybeans, at temperatures ranging from 10°C to 40°C, the Page equation gave a slightly better fit than the finite surface resistance diffusion model in the only three cases that were compared (Osborn et al., 1991). With only three cases, the comparison was limited, and Bi_m in the finite surface resistance diffusion equation was not completely optimized to provide the best fit; thus there was little evidence that the finite surface resistance diffusion equation did not fit soybean adsorption data as well as the Page equation below 40°C. All of the wheat and barley tests reported here were conducted at 15°C and 30°C, and the two types of equations fit equally well. In the desorption data of Walton et al. (1988), which had a wide range of temperatures (38°C to 104°C), the Page equation had noticeably higher standard errors at temperatures of 55°C and above, while it usually fit the data nearly as well as the finite surface resistance diffusion equation at 38°C. Thus, for corn desorption, the finite surface resistance diffusion equation offered the best advantage over the Page equation at higher

Table 2. Standard errors of regression for six candidate equations with wheat kernels.

Test Conditions	Average standard error of regression for 3 replications (units of MR)					
	Exponential drying equation	Page equation	Spherical standard diffusion	Cylindrical standard diffusion	Spherical cellular diffusion	Cylindrical cellular diffusion
30°C, 50% rh	0.034	0.0217	0.054	0.047	0.0211	0.0212
30°C, 71% rh	0.012	0.0104	0.067	0.058	0.0092	0.0089
30°C, 78% rh	0.010	0.0049	0.065	0.057	0.0049	0.0046
15°C, 58% rh	0.029	0.0172	0.049	0.045	0.0172	0.0170
15°C, 78% rh	0.016	0.0094	0.062	0.054	0.0104	0.0106
15°C, 85% rh	0.019	0.0062	0.056	0.047	0.0062	0.0063
Average	0.020	0.0116	0.059	0.051	0.0115	0.0114

Table 3. Standard errors of regression for six candidate equations with barley kernels.

Test Conditions	Average standard error of regression for 3 replications (units of MR):					
	Exponential drying equation	Page equation	Spherical standard diffusion	Cylindrical standard diffusion	Spherical cellular diffusion	Cylindrical cellular diffusion
30°C, 50% rh	0.060	0.0121	0.022	0.018	0.0122	0.0140
30°C, 71% rh	0.051	0.0067	0.026	0.020	0.0076	0.0081
30°C, 78% rh	0.036	0.0122	0.038	0.030	0.0112	0.0099
15°C, 58% rh	0.031	0.0067	0.017	0.016	0.0075	0.0073
15°C, 78% rh	0.049	0.0120	0.027	0.021	0.0115	0.0098
15°C, 85% rh	0.017	0.0044	0.035	0.034	0.0050	0.0048
Average	0.041	0.0090	0.028	0.023	0.0092	0.0090

Table 4. Adsorption parameters for exponential drying equation and Page equation.

Test Conditions	Wheat			Barley		
	Page equation		Exp. equation	Page equation		Exp. equation
	K, $h^{-1/n}$	n	(k, h^{-1})	K, $h^{-1/n}$	n	(k, h^{-1})
30°C, 50% rh	0.162	0.862	0.119	0.207	0.694	0.102
30°C, 71% rh	0.198	0.968	0.187	0.166	0.720	0.083
30°C, 78% rh	0.196	0.949	0.179	0.158	0.810	0.099
15°C, 58% rh	0.082	0.838	0.053	0.079	0.675	0.024
15°C, 78% rh	0.102	0.923	0.083	0.081	0.726	0.032
15°C, 85% rh	0.105	0.896	0.080	0.049	0.835	0.032

Note: Corresponding standard errors of regression are listed in tables 2 and 3.

temperatures (above 40°C). The existing adsorption data (soybeans, wheat, and barley) were limited to lower tem–peratures but were consistent with the same temperature effect seen for corn desorption.

As in other applications, the exponential drying equation was not able to describe the data as well as the Page or cellular–based finite surface resistance diffusion equations. Although there was more external resistance to moisture than with typical higher temperature and higher airflow drying tests, the internal resistance was still large enough that the negligible internal resistance assumption of the exponential drying equation was not accurate. This may be quantified by looking at the Biot numbers for the cylindrical diffusion equation (noting that Bi_m is the ratio of internal to external resistance, so that smaller magnitudes of Bi_m indicate larger external resistance, although it is external resistance relative to the corresponding D' rather than a direct measure). Even the lowest Biot numbers were greater than 1.0, indicating that the majority of the resistance to adsorption was internal rather than external. The two lowest Biot numbers in table 6 were about 1.6 (wheat at 30°C; 71% and 78% relative humidity), and the exponential drying equation fit the data reasonably well in that case. The Biot numbers, shown in table 5 and 6, for the finite surface resistance diffusion models ranged from 1.6 to 40. The smaller Biot numbers in this range indicated that, while the majority of the resistance was internal (since $Bi_m > 1$), there was still an important portion of the total resistance to moisture transfer that was external to cells of the endosperm and germ (since $Bi_m < 100$).

The exponential drying equation fit the wheat data better than the zero surface resistance diffusion equations in every case in table 2, but did not fit the barley data as well as the zero surface resistance diffusion equations in the majority of cases in table 3. These differences were all consistent with the theoretical significance of the Biot numbers shown in table 5 and 6. The exponential drying equation fit better than the zero surface resistance diffusion equations in cases with smaller Biot numbers, while the zero surface resistance diffusion equations fit better for cases with larger Biot numbers.

The zero surface resistance diffusion equations, using the assumption of negligible external resistance, did not describe the data as well as the Page or cellular–based finite surface resistance diffusion equations. As mentioned, they fit the data better than the exponential drying equation in cases with relatively large Biot numbers, matching their theoretical basis. These equations showed a better fit with the barley tests than with wheat. This is due to there being less external resistance for barley kernels, as indicated by the higher Biot numbers for barley that were determined with the finite surface resistance diffusion equations (tables 5 and 6). The finite surface resistance diffusion equations, which could fit different Biot number cases equally well, did not exhibit nearly as much difference between the wheat and barley kernels.

Table 7 compares the adsorption rate and diffusion parameters for a set of tests with different airflow rates. The adsorption rate (indicated by half–response time) was significantly lower for barley compared to wheat; the affect

Table 5. Diffusion coefficients and Biot numbers for spherical diffusion equations.

Test Conditions	Wheat			Barley		
	Standard eq. (D'/R^2, h^{-1})	Cellular eq. (D'/R^2, h^{-1})	Cellular eq. (Bi_m)	Standard eq. (D'/R^2, h^{-1})	Cellular eq. (D'/R^2, h^{-1})	Cellular eq. (Bi_m)
30°C, 50% rh	0.0069	0.0179	6.20	0.0057	0.0069	30.5
30°C, 71% rh	0.0112	0.0528	1.57	0.0045	0.0060	21.0
30°C, 78% rh	0.0104	0.0647	1.90	0.0059	0.0096	9.0
15°C, 58% rh	0.0023	0.0063	6.07	0.0006	0.0009	33.5
15°C, 78% rh	0.0048	0.0161	2.67	0.0017	0.0023	20.0
15°C, 85% rh	0.0047	0.0125	3.83	0.0019	0.0026	4.2

Note: Corresponding standard errors of regression are listed in tables 2 and 3.

Table 6. Diffusion coefficients and Biot numbers for cylindrical diffusion equations.

Test Conditions	Wheat			Barley		
	Standard eq. (D'/R^2, h^{-1})	Cellular eq. (D'/R^2, h^{-1})	Cellular eq. (Bi_m)	Standard eq. (D'/R^2, h^{-1})	Cellular eq. (D'/R^2, h^{-1})	Cellular eq. (Bi_m)
30°C, 50% rh	0.0136	0.0298	6.10	0.0112	0.0126	41.3
30°C, 71% rh	0.0219	0.0838	1.57	0.0089	0.0111	23.3
30°C, 78% rh	0.0204	0.0814	1.63	0.0114	0.0168	9.8
15°C, 58% rh	0.0047	0.0112	5.33	0.0013	0.0020	26.0
15°C, 78% rh	0.0094	0.0262	2.60	0.0034	0.0042	23.7
15°C, 85% rh	0.0092	0.0207	3.03	0.0055	0.0062	4.4

Note: Corresponding standard errors of regression are listed in tables 2 and 3.

Table 7. Adsorption results for different airflow rates (averages of three replications).

Airflow Rate	Wheat			Barley		
	$t_{1/2}$, h	D'/R^2, h^{-1}	Bi_m	$t_{1/2}$, h	D'/R^2, h^{-1}	Bi_m
Still air	14.3	0.0161	2.43	26.4	0.0050	6.33
0.16 m/s	8.2	0.0207	3.03	24.0	0.0062	11.10
0.32 m/s	6.9	0.0277	2.85	25.7	0.0030	27.67

of airflow was also significant in the analysis of variance ($P \leq 0.01$). The effect of higher airflows was particularly prominent with wheat kernels. The barley kernels, with their uniformly lower external resistance than wheat kernels, showed a much smaller effect of airflow on adsorption rate. Using Duncan's new multiple range test, the adsorption rate means from the data in table 7 were significantly different for still air ($P \leq 0.01$), while adsorption rate means at the two higher airflows were not significantly different from each other ($P \leq 0.05$).

These data were similar to thin–layer desorption data, but the rates were generally lower than for desorption. In figure 2, two adsorption tests for barley are compared to two corresponding desorption tests over a similar range of moisture content, showing the Page equation averaged over three replications. The adsorption test required more time than the desorption test to achieve the same change in moisture content. The average values for three replications are compared in table 8. These averages, as well as all twelve of the individual desorption tests (six of wheat and six of barley), had faster rates than the corresponding adsorption tests. Analysis of variance of the data in table 8 showed that all three factors, temperature, grain type, and direction (adsorption vs. desorption), had a significant effect on the rate of adsorption or desorption ($P \leq 0.01$).

Comparing the half–response times in tables 7 and 8 reveals that the barley kernels adsorbed moisture at significantly lower rates than did the wheat kernels at all twelve adsorption conditions. Barley is known to dry slower than wheat (with the husk suspected as the cause) and was expected to also have lower adsorption rates than wheat, as was found. Tables 5 and 6 show that the lower adsorption rates for barley were reflected in lower diffusion coefficients, while the Biot numbers were uniformly higher for barley as compared to wheat. Thus, barley kernels had greater internal resistance and less external resistance than did wheat kernels. Of the two resistances, the higher internal resistance dominated the total resistance, yielding lower adsorption rates for barley.

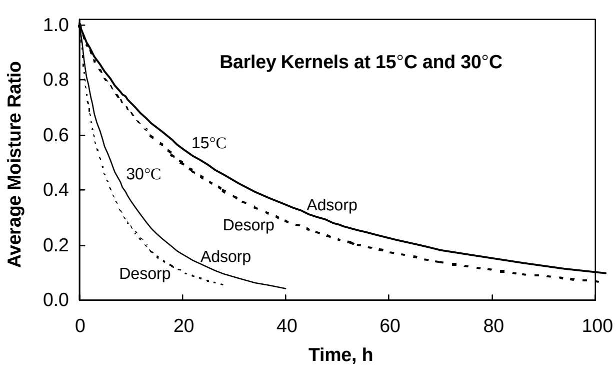

Figure 2. Comparison of adsorption and desorption at two temperatures using the Page equation from an average of three replications for each.

Table 8. Adsorption and desorption half–response times ($t_{1/2}$) from the Page equation (average half–response timein hours for three replications).

	Wheat		Barley	
Temp.	Adsorption	Desorption	Adsorption	Desorption
30°C	3.78	3.14	6.22	4.23
15°C	8.20	6.59	24.0	18.8

These higher Biot numbers for barley may seem contrary to the physical situation of the extra layer (husk) on the barley kernel. However, an evaluation of the kernel microstructure indicates apparent reasons why the husk does not in fact offer additional resistance to moisture transfer. While the aleurone layer contains significant interconnected pore space that provides negligible resistance to moisture transfer, the pericarp offers significant resistance to moisture transfer (MacMasters, 1962). The minor bran layers (seed coat and nucellar epidermis) may behave like the pericarp, except for being much thinner (Hinton, 1955). Walton et al. (1988) and Muthukumarappan and Gunasekaran (1994) found significant moisture resistance in the pericarp to desorption and adsorption, respectively, in corn kernels, a naked caryopsis like wheat. However, in a limited study, Babbitt (1949) suggested that the pericarp resistance to adsorption was negligible for wheat kernels. Hinton (1955) indicated that it was the seed coat, between the aleurone and pericarp, that provided the greatest resistance to liquid water absorption during tempering of wheat. The presence of a husk has been suggested as the reason rice dries more slowly than wheat (Brooker et al., 1992).

While the seed coat and pericarp consist of a tight arrangement of cells that offers very high resistance to moisture (Hoseney and Faubion, 1992; MacMasters, 1962; Syarief at al., 1987), the barley husk is much more porous than the pericarp and seed coat because of wider spacing between cells. This porous structure should make it more like the aleurone layer, as far as moisture movement is concerned, which is thought to have negligible resistance to moisture transfer (MacMasters, 1962; Walton et al., 1988). Thus, the cell structure is consistent with the results of slower moisture movement in barley kernels resulting from lower diffusion coefficients for the endosperm and germ, while the total resistance of the bran and husk was actually less than the resistance of the bran alone in wheat. Therefore, the greater external resistance found for wheat kernels was from the higher resistance of the bran of wheat, as compared to that of barley, and there may have been no additional resistance to moisture transfer from the barley husk.

It is also possible that the barley husk even provided a fin effect for moisture transfer. This would have enhanced moisture transfer at the surface and reduced the surface resistance as compared to a kernel with no husk, as was indicated by the higher Biot numbers for barley as compared to wheat that always occurred in the data (tables 5 and 6). (Since the Biot number was the ratio of internal to external resistance, the Biot number had to be combined with diffusion coefficients in tables 5 and 6 to arrive at a direct measure of external resistance. This required determining kernel densities and the average slope of the equilibrium moisture isotherm for each grain type and ambient condition in the data. Required data were available from ASAE (*ASAE Standards,* 1994c, 1994d). These tedious calculations were done for all conditions in tables 5 and 6, and the external resistance of barley kernels was less than wheat kernels in every case, as suggested by the Biot numbers alone.)

The relative goodness of fit of the different geometric–shape zero surface resistance diffusion equations is largely explained by the actual geometry of the kernels. The zero surface resistance cylindrical model gave a better fit for both wheat and barley kernels than the zero surface resistance spherical model; this was expected, since both kernels have a more nearly cylindrical than spherical shape. Furthermore, the cylindrical models demonstrated a much greater improvement over spherical models for barley kernels than for wheat kernels. Again, this would be expected, since barley kernels have an even more distinctly cylindrical shape than wheat kernels. However, the cellular–based finite surface resistance diffusion equations did not show any clear trends between the different geometry models. As noted in Walton and Casada (1986), this is probably due to the geometry having less impact on the model than the proper characterization of the resistances to moisture transfer.

CONCLUSIONS

Moisture adsorption parameters for wheat and barley during storage were determined for six candidate equations. Analysis of the moisture adsorption data and representative desorption data using the model thin–layer adsorption equations yielded the following conclusions:

- The Page equation and the cellular–based finite surface resistance diffusion equations described the adsorption data for wheat and barley better than the other tested models.
- Moisture adsorption in wheat and barley kernels was significantly slower than desorption rates in these tests.
- The external resistance to moisture transfer (including bran, husk, and convection) in wheat and barley kernels was not negligible, but provided an important minority of the total resistance to moisture transfer.
- The bran on the wheat kernels offered significantly more external resistance to moisture movement than the bran and husk combined on barley kernels, while the endosperm and germ of barley kernels offered significantly more internal resistance than that of wheat kernels.

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NOMENCLATURE

n, k, K = experimental constant for empirical equations

t = time (s)

$t_{½}$ = half–response time for adsorption or desorption (time required for $\overline{MR}$ to reach 0.5) (s)

$$A_n = \frac{[\sin(\lambda_n R) - \lambda_n R \cdot \cos(\lambda_n R)]^2}{(\lambda_n R)^3 [\lambda_n R - \sin(\lambda_n R) \cdot \cos(\lambda_n R)]}$$ = constant in spherical diffusion equation

$$B_n = \frac{J_1(\lambda_n R)}{(\lambda_n R) \cdot [(\lambda_n R)^2 + Bi_m^2] J_0(\lambda_n R)}$$ = constant in cylindrical diffusion equation

Bi_m = modified Biot number for mass transfer (dimensionless)

D' = modified mass diffusion coefficient ($m^2\ s^{-1}$)

J_0 , J_1 = Bessel functions of the first kind and order zero and one, respectively

$\overline{MR}$ = $(M - M_e)/(M_o - M_e)$ = average moisture ratio (dimensionless)

M = average moisture content at any time, decimal dry basis

M_e = equilibrium moisture content, decimal dry basis

M_o = average initial moisture content, decimal dry basis

R = equivalent radius of sphere or cylinder (m)

λ_n = eigenvalues for diffusion equations