Relating Drying Rate Constant to Head Rice Yield Reduction of Long-grain Rice

H. Chen, T. J. Siebenmorgen, B. P. Marks

Abstract. *Long-grain rough rice was dried at various rates and durations and milled to determine head rice yield. The drying data were described by a Newton equation, and the resultant head rice yield reduction data were described by an empirical rate equation. Effects of drying condition, variety, harvest moisture content, and storage time prior to drying were investigated, but only the first two of those variables significantly affected the drying rate constant, and the first three of those variables significantly affected the head rice yield reduction. Head rice yield reduction was directly related to the drying rate constant. At a given drying rate constant, head rice yield reduction increased with drying duration. An empirical model was developed to predict the head rice yield reduction as a function of drying rate constant and drying duration. This model may lead to optimal control of rice dryers in terms of minimizing head rice yield reduction during the drying process.* **Keywords.** *Rice drying, Drying rate constant, Head rice yield reduction.*

Rice is generally harvested at a moisture content (MC) of 19 to 28% dry basis (d.b.)†, and is typically dried to approximately 15% MC or lower to inhibit fungi and insects for safe storage. Rice drying is normally performed by passing heated air through the rice to evaporate moisture. Extensive single kernel and thin-layer drying research has been conducted to characterize and predict the rice drying process (Noomhorm and Verma, 1986; Jindal and Siebenmorgen, 1987; Banaszek and Siebenmorgen, 1993). Many drying equations have been obtained, of which the ASAE Standards (ASAE, 1995) lists Page's equation for grains and crops:

$$\frac{\mathrm{MC} - \mathrm{EMC}}{\mathrm{IMC} - \mathrm{EMC}} = \exp\left(-k \times t^{n}\right) \qquad (1)$$

where MC is the moisture content of the grain (decimal dry basis, dec. d.b.) at drying time t (h), EMC is the equilibrium moisture content (dec. d.b.), IMC is the initial moisture content (dec. d.b.), k is the drying rate constant (h^{-1}), and n is a dimensionless constant. The drying rate constant k is an important parameter reflecting the rate at which water from the kernel is removed. Kachru et al. (1970) found that k was a characteristic of the grain. Henderson and Pabis (1961) pointed out that k was related to drying temperature. Allen (1960) concluded that k was a function of the initial and instantaneous MC of the grain, as well as the drying air conditions including temperature, relative humidity (RH) and air flow rate. Banaszek and Siebenmorgen (1993) developed a model to predict k using rice kernel size and harvest moisture content (HMC).

Due to the fact that rice is used primarily as a food product, kernel quality is of utmost importance. The primary physical quality index is head rice yield (HRY). Head rice yield is the mass percentage of rough rice that remains as head rice after milling; head rice is milled rice kernels that are three-fourths of the original kernel length after complete milling (USDA, 1979). Minimizing HRY reduction (HRYR) during drying is of primary interest to the rice industry. Improper drying can produce kernel fissures, which structurally weaken the kernel and make it more susceptible to breakage during subsequent hulling and milling processes. Improper moisture and temperature changes in the kernel during drying are major sources of rice fissures. It has been reported that moisture gradients in the rice kernel create unequal swelling or shrinking within the rice kernel, which may induce rice fissures (Rhind, 1962; Kunze, 1979). Henderson (1954) discovered that rice fissures during rapid drying were due to an increase in temperature rather than a decrease in moisture near the kernel surface. Arora et al. (1973) concluded that fissures occurred when a certain level of temperature gradient existed between the drying air and the rice kernel. Mossmann (1986) suggested that drying temperature did not affect kernel fissures if the drying rate was held to a minimum.

Previous studies have indicated the effects of various factors on drying rate constants and on the development of rice fissures. However, none quantified the relationship between HRYR and drying parameters, including drying rate constant and drying duration. Therefore, the objectives of this work were to:

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† Unless otherwise specified, all moisture contents mentioned herein are on a dry basis.

1. Mathematically describe experimental drying data and resultant HRYR data;
2. Quantify the effects of drying air condition, harvest rice moisture content, variety, and storage time prior to drying on drying rate constant k and HRYR; and
3. Relate HRYR to drying rate constant and drying duration.

Experimental Procedure

Six long-grain rice variety/harvest MC (HMC) combinations (Lacassine/26.5%, Millie/26.5%, Alan/30%, Alan/23.5%, Newbonnet/37%, and Newbonnet/23.5%) were harvested from Stuttgart and Keiser, Arkansas, in September and October 1993. The rice was immediately cleaned in a dockage machine to remove foreign material. Part of the cleaned rice from each variety/HMC was placed in large plastic bags, sealed to prevent moisture loss, and kept at room temperature (approximately 20°C) for immediate drying tests (1 to 2 days from arrival). The remaining cleaned rice was placed in large sealed plastic bags and stored at 1°C for four months. Prior to the drying tests, cold rice samples were removed from storage and allowed to equilibrate overnight in sealed plastic bags to room temperature.

Drying tests were carried out in the system described by Siebenmorgen and Banaszek (1988). The system consisted of a drying chamber in which air conditions were controlled by a temperature and RH control unit (Parameter Generation and Control 300 CFM Climate-Lab-AA). Inside the chamber, sixteen, 152 × 254 mm trays with perforated bottoms were arranged in parallel to hold rice samples. Drying air with the desired RH and temperature from the control unit was introduced into a plenum at the bottom of the chamber, passed through the rice samples, and returned to the control unit to form a closed-loop circulation pattern. Air conditions in the plenum were monitored with an RH and temperature monitoring system.

Four drying air conditions and one control air condition, as depicted in the psychrometric chart representation of figure 1, were used in the tests, where EMC was the equilibrium moisture content calculated using Chung's equation (ASAE, 1995). The control air condition was set at an EMC of 14.3% using the indicated temperature and RH, which are typical of ambient conditions during the harvest season at Stuttgart, Arkansas. Conditions B and D represent air conditions used in conventional drying processes through fossil fuel combustion using intake air at the indicated control temperature and RH. Conditions A and C represent the air conditions that would exist if control air was conditioned in a desiccant drier. Conditions A and C would theoretically dry the rice to the same EMC as conditions B and D, respectively, but at lower temperature and RH (fig. 1).

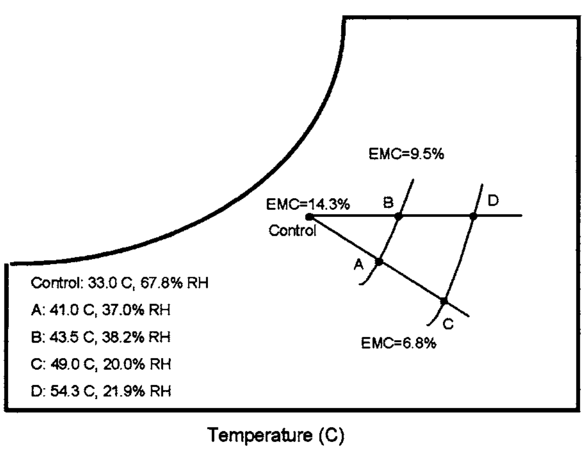

Figure 1–Psychrometric representation of the drying and control air conditions used in the drying tests.

Sixteen, 550 g samples of each variety/HMC/storage time were selected using a Boerner divider and randomly placed in the 16 trays of the conditioning chamber. Two samples were removed at 15 min intervals for the first hour and at 1 h intervals for the remaining three hours of the testing period. To maintain the same drying air distribution inside the drying chamber, "dummy" samples of the same sample weight were placed into the empty trays to replace the removed samples. From each removed sample, one 15 g subsample was removed for oven moisture content tests (130°C, 24 h). The remainder of the two removed samples at each of the specified drying durations were combined and placed in a conditioning chamber similar to the drying chamber to allow the rice to gradually approach a MC of 13.5 to 15%. The equilibrated samples were removed from the conditioning chamber, sealed in plastic bags and held in a cold storage room at 1°C for further milling tests.

Milling quality was evaluated in terms of HRY and degree of milling (DOM). Prior to the milling tests, samples were removed from cold storage and held at room temperature for about 24 h. Four 150 g subsamples from each sample were hulled separately using a sample huller (McGill) and milled for either 15, 30, 45, or 60 s in a laboratory rice mill (McGill No. 2). The mill was equipped with a 1500 g mass placed on the mill lever arm 150 mm from the centerline of the milling chamber. After milling, the broken rice was removed using a shaker-sizer (Seedburo Equip. Corp.). The HRY was calculated as the percentage of the original 150 g rough rice mass that remained as head rice. DOM of the head rice was measured using a milling meter (Satake, model MM-1B), which operates on the basis of optical reflectance and transmittance from the subsample. The DOM value may range from 0 to 199, with 0 corresponding to brown rice and 199 to well-milled white rice. A meter DOM reading of 90 is typical of the level desired by rice processors. There exists a negative linear relationship between HRY and DOM (Sun and Siebenmorgen, 1993). From the milling data of the four subsamples, a linear equation between HRY and DOM was established for each sample. The HRY at a DOM of 90 was determined from the equation and used as the HRY of each sample for analysis.

Results and Discussion

Drying Data and Drying Rate Constant

Drying data were described by the following Newton equation:

$$MC = (A - EMC) \times \exp(-k \times t) + EMC \qquad (2)$$

with t being in h, k in h^{-1} , and A a regression constant in percent d.b. Ideally, constant A should be equal to the MC at the initiation of drying. Compared with equation 1, this model assumed that n equaled 1 (Noomhorm and Verma, 1986; Banaszek and Siebenmorgen, 1993).

The NLIN least squares procedure of SAS (SAS Institute, 1987) was used to determine A and k of equation 2 from the experimental data. Variance analysis was carried out by using the GLM procedure of SAS, in which drying condition (4 levels: A, B, C, D), variety (4 levels: Lacassine, Millie, Alan, Newbonnet), HMC (2 levels: those with HMC over 25% were classified as high MC; those with HMC under 25% were classified as medium MC), storage (2 levels: dried immediately after harvest represented by Stg.1 and stored for 4 months at 1°C prior to drying represented by Stg.2), and drying trial repetition (2 levels: 2 repetitions) were regarded as major factors. Statistical results are illustrated in table 1. At the 0.05 significance level, drying condition and variety were significant factors affecting the k value. The drying condition×storage interaction was the only interaction term significantly affecting the k value. Table 2 shows the mean k values and associated standard deviations (SDs) for each of these two factors and the drying condition×storage interaction, where each mean value represents the average k value across all experimental data at the corresponding factor level. Figure 2 illustrates the experimental drying data and the fitted models at the four drying air conditions, with each experimental point being the average of all experimental data at the associated drying duration and condition. It is indicated in figure 2 that a larger k value represents a more rapid drying process. It may also be found from figure 2 that calculated A values in equation 2, which were represented by the fitted curve points at time 0, were a little lower than the overall HMC, which was 27.9%.

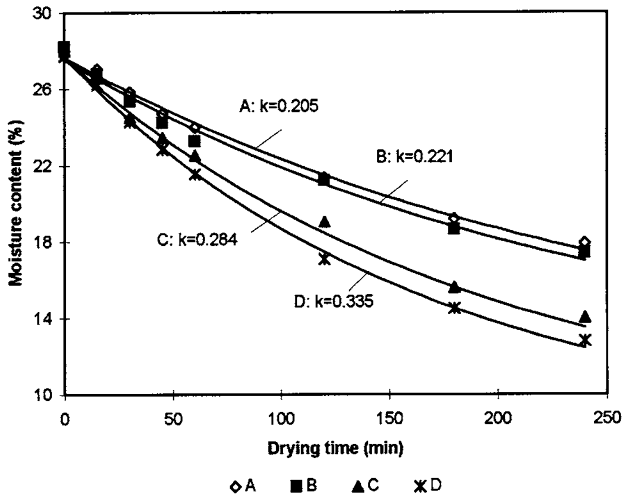

Figure 2–Overall experimental drying data averaged over each of the four indicated drying air conditions (fig. 1) and fitted curves using equation 2.

Table 1. Variance analysis on the drying rate constant k (DC: drying air condition; HMC: harvest moisture content; Var: variety; Stg: storage time before drying; Rep: repetition)

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F value	Probability Value α
DC	3	0.2585	0.0862	105.79	0.0001*
HMC	1	0.0005	0.0005	0.60	0.4417
Var	3	0.0505	0.0168	20.67	0.0001*
Stg	1	0.0002	0.0002	0.27	0.6048
Rep	1	0.0001	0.0001	0.16	0.6928
HMC×Stg	1	0.0006	0.0006	0.72	0.3993
HMC×DC	3	0.0013	0.0004	0.53	0.6659
Var×DC	9	0.0066	0.0007	0.91	0.5250
DC×Stg	3	0.0241	0.0080	9.85	0.0001*
Error	70	0.0570	0.0008		
Total	95	0.3994			

* Means significant at 0.05 level.

Table 2. Arithmetic means and standard deviation of k values for the significant factors in table 1 (DC: drying condition; Var: variety; Stg: storage)

Factors	Levels	Mean (h^{-1})	SD	Factors	Levels		Mean (h^{-1})	SD
DC	A	0.205	0.033	DC×Stg	A	Stg.1	0.218	0.030
	B	0.221	0.036			Stg.2	0.193	0.032
	C	0.284	0.047		B	Stg.1	0.203	0.033
	D	0.335	0.040			Stg.2	0.240	0.030
Var	Lacassine	0.278	0.063		C	Stg.1	0.268	0.053
	Alan	0.286	0.062			Stg.2	0.300	0.034
	Millie	0.249	0.067		D	Stg.1	0.351	0.026
	Newbonnet	0.234	0.058			Stg.2	0.319	0.045

Drying conditions A and B had lower k values than C and D (table 2). Checking the EMCs of the four drying conditions (fig. 1) led to the primary conclusion that k values are inversely related to EMC. A pairwise t-test showed that even at the same EMC of 6.8%, condition D resulted in a significantly (α = 0.05) larger k value than did condition C. Compared with drying condition C, the same EMC at condition D was predicted by Chung's equation (ASAE, 1995) but with higher air temperature and RH. Hence, for the same EMC, higher temperature and/or RH may cause higher k values. This trend was also apparent between drying conditions A and B. However, a pairwise t-test for k values between conditions A and B showed a probability value (α) of 0.06, which indicated that the difference in k values between A and B was not significant. The dependence of k on air temperature and RH corresponding to a given EMC was less at the lower EMC level.

Variety was the second significant contributor affecting k. Alan had the highest k value, and Newbonnet the lowest.

As a single factor, storage time prior to drying had no significant effect on k value, i.e., rice dried at the same rate immediately after harvest as it did after four months of storage at 1°C. However, the interaction of storage×drying condition produced different k values. At drying condition A, stored rice (Stg.2) had a lower k value than non-stored rice, while at drying condition B, it was the inverse. This trend also existed for conditions D and C.

Repetition was treated as a factor to examine if measurement errors or some uncontrollable factors in measurements were within acceptable range. Insignificance of this factor (α = 0.69) indicated that measurement errors could be ignored.

HEAD RICE YIELD REDUCTION DATA AND MODEL

HRYR is defined as the difference, expressed in percentage points, between the HRY at the beginning of drying and the HRY at a given drying duration t. The HRYR data were described by the following empirical rate equation:

$$\text{HRYR} = \frac{t}{\beta_0 + \beta_1 \times t} \quad (3)$$

where t is in h, and β_0 and β_1 are regression coefficients. The model was used by Banaszek and Siebenmorgen (1990) to predict the HRYR of rough rice caused by moisture adsorption. The first derivative of HRYR with respect to t can be referred to as the HRYR rate and is equal to $1/\beta_0$ when t is at 0. Thus β_0 determines the initial HRYR rate, with a larger β_0 corresponding to a smaller rate. β_1 can be regarded as a coefficient reflecting the divergence of a HRYR curve from a line with constant slope equaling the initial HRYR rate. Figure 3 exhibits the average of all experimental HRYR data and the associated fitted equations based on equation 3 for each of the four drying conditions. A larger β_1 value led, in general, to an increased divergence from the initial HRYR rate towards lower HRYR values. The curves show that the overall rate of HRYR was greatest for condition D (EMC = 6.8%), followed by condition C (EMC = 6.8%), and was equal for conditions A and B representing the 9.5% EMC.

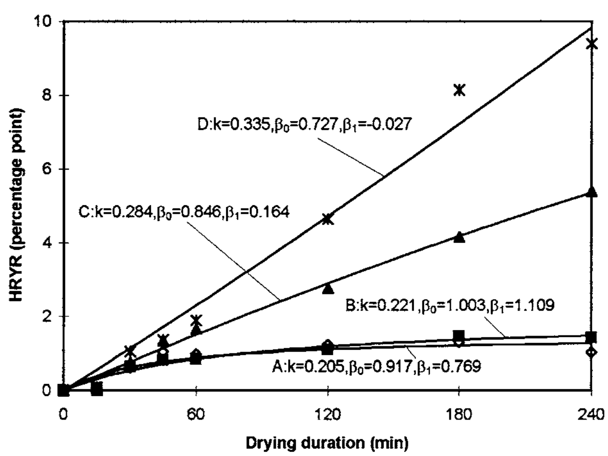

Figure 3–Overall experimental head rice yield reduction (HRYR) data averaged over each of the four drying air conditions (fig. 1) and associated fitted curves using equation 3.

The same statistical methods mentioned above were used for determining β_0 and β_1 in equation 3, as well as for the associated variance analysis on these two parameters. HRYRs were calculated from equation 3 at the drying durations of 30, 90, 180, and 240 min (referred to as HRYR30, HRYR90, HRYR180, and HRYR240, respectively) for each specific drying test. Table 3 presents F values and probability values of these five factors (drying condition, HMC, variety, storage, and drying trial repetition) and their major interactions. Table 4 presents the means and SDs of the factors and interactions which significantly (at 0.05 significance level) affected β_0 and β_1, while table 5 presents the means and SDs of the factors and interactions which significantly affected HRYR30, HRYR90, HRYR180, and HRYR240.

Variety was the only factor affecting β_0. Newbonnet had the highest β_0, and Millie had the lowest β_0 (table 4). Luh (1980) indicated that the initial drying stage, which is short and occurs at the start of drying, is characterized by warm-up of the rice. Little HRYR may occur during this stage. This may explain why other factors such as HMC and drying condition did not influence β_0. HMC and drying condition affected β_1. A higher HMC corresponded to a lower β_1 than did the medium HMC. Drying conditions A and B had higher β_1 values than C and D. No interaction was found to significantly influence β_0 and β_1.

Due to both β_0 and β_1, the HRYRs at various drying durations were significantly influenced by drying condition, variety, and HMC as well as by the interactions of drying condition with HMC, variety, and storage. Increasing drying duration resulted in considerably higher F values of these factors (table 3), implying that greater HRYRs resulted from longer drying duration.

Table 5 indicates that under drying conditions A and B, HRYRs were 0.55 to 0.60 percentage points (pp) after 30 min of drying and were increased to 1.4 to 1.6 pp for 240 min; whereas, under C and D, HRYRs were 0.9 to 1.2 pp for 30 min and 5.5 to 10.0 pp for 240 min. Drying conditions C and D had higher HRYRs than A and B. The HRYRs caused by the four drying conditions were much smaller at drying duration 30 min than at 240 min. HRYRs increased much more with drying duration at conditions C and D than at A and B. It was noted that drying condition D caused much higher HRYR than did C, even though both represented the same EMC, suggesting that HRYR was

Table 3. Variance analysis on β_0, β_1, and head rice yield reductions (HRYR) (variable abbreviations are listed in table 1)

Source		DC	HMC	Var	Stg	Rep	HMC×Stg	HMC×DC	Var×DC	DC×Stg
β_0	F	0.43	0.82	3.53	0.71	0.08	0.00	1.10	1.03	1.55
	α	0.7335	0.3795	0.0191*	0.4010	0.7778	0.9770	0.3530	0.4259	0.2104
β_1	F	12.93	11.55	0.45	0.26	0.66	1.01	1.91	1.10	0.19
	α	0.0001*	0.0011*	0.7180	0.6096	0.4204	0.3174	0.1366	0.3774	0.9033
HRYR30	F	9.32	7.13	4.88	1.97	0.14	0.16	2.73	2.29	7.05
	α	0.0001*	0.0094*	0.0039*	0.1645	0.7073	0.6875	0.0501*	0.0255*	0.0003*
HRYR90	F	30.95	20.97	7.03	2.89	0.37	0.02	5.15	2.49	7.65
	α	0.0001*	0.0001*	0.0003*	0.0938	0.5459	0.8811	0.0028*	0.0157*	0.0002*
HRYR180	F	71.61	49.35	15.80	2.69	0.29	0.01	12.26	4.70	7.30
	α	0.0001*	0.0001*	0.0001*	0.1052	0.5915	0.9248	0.0001*	0.0001*	0.0003*
HRYR240	F	124.33	88.92	28.44	0.66	0.02	0.37	22.82	8.11	5.98
	α	0.0001*	0.0001*	0.0001*	0.4178	0.8991	0.5474	0.0001*	0.0001*	0.0011*

* Means significant at 0.05 level.

Table 4. Arithmetic means and standard deviation of β_0 and β_1 values for the significant factors in table 3 (variable abbreviations are listed in table 1)

		β_0		β_1	
Factors	Levels	Mean	SD	Mean	SD
DC	A			0.70	0.66
	B			1.11	1.28
	C			0.16	0.43
	D			–0.03	0.15
HMC	H			0.33	0.72
	M			0.86	1.04
Variety	Lacassine	0.92	0.91		
	Alan	0.63	0.61		
	Millie	0.62	0.48		
	Newbonnet	1.23	1.18		

Table 5. Arithmetic means and standard deviations of head rice yield reductions (HRYR) at 30, 90, 180, and 240 min drying duration for the significant factors in table 3 (variable abbreviations are listed in table 1)

			HRYR30		HRYR90		HRYR180		HRYR240	
Factors	Levels		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DC	A		0.63	0.46	1.00	0.53	1.27	0.62	1.39	0.71
	B		0.55	0.43	0.98	0.80	1.36	1.13	1.59	1.36
	C		0.89	0.54	2.24	1.41	4.05	2.74	5.45	4.08
	D		1.20	0.85	3.50	2.38	7.07	4.53	9.97	6.04
HMC	H		0.91	0.71	2.28	2.00	4.24	4.05	5.81	5.72
	M		0.63	0.42	1.23	0.88	1.83	1.46	2.18	1.90
Variety	Lacassine		1.07	0.92	3.09	2.77	6.43	5.78	9.19	8.24
	Alan		0.93	0.61	2.04	1.52	3.24	2.81	4.08	3.77
	Millie		0.79	0.33	1.78	1.24	3.13	2.89	4.08	4.24
	Newbonnet		0.56	0.52	1.32	1.35	2.30	2.33	3.08	3.11
HMC×DC	H	A	0.62	0.47	1.03	0.53	1.34	0.63	1.49	0.74
		B	0.63	0.48	1.19	0.89	1.71	1.22	2.02	1.47
		C	0.93	0.60	2.57	1.51	4.96	2.78	6.93	4.12
		D	1.45	0.89	4.33	2.45	8.96	4.39	12.80	5.39
	M	A	0.65	0.47	0.95	0.56	1.12	0.61	1.18	0.64
		B	0.38	0.23	0.56	0.34	0.68	0.41	0.72	0.45
		C	0.80	0.43	1.58	0.97	2.23	1.54	2.50	1.82
		D	0.70	0.46	1.83	0.96	3.29	1.33	4.33	1.74
DC×Stg	A	Stg.1	0.72	0.52	1.10	0.57	1.36	0.66	1.49	0.77
		Stg.2	0.55	0.39	0.90	0.49	1.17	0.59	1.29	0.65
	B	Stg.1	0.37	0.17	0.73	0.34	1.17	0.80	1.49	1.26
		Stg.2	0.72	0.54	1.23	1.04	1.56	1.39	1.68	1.51
	C	Stg.1	0.83	0.55	2.08	1.46	3.66	2.87	4.69	3.93
		Stg.2	0.95	0.56	2.40	1.40	4.43	2.67	6.22	4.25
	D	Stg.1	1.62	0.85	4.55	2.43	8.62	4.79	11.33	6.47
		Stg.2	0.78	0.64	2.45	1.87	5.52	3.85	8.62	5.52
Var×DC	Laca-ssine	A	0.42	0.24	1.00	0.52	1.62	0.86	1.96	1.10
		B	0.64	0.59	1.30	1.11	1.93	1.39	2.27	1.47
		C	1.07	0.50	3.46	1.29	8.04	1.87	12.45	2.67
		D	2.14	1.10	6.60	2.92	14.11	4.56	20.11	4.70
	Alan	A	0.97	0.58	1.39	0.54	1.65	0.44	1.76	0.40
		B	0.62	0.54	1.07	1.10	1.36	1.48	1.46	1.61
		C	1.33	0.50	2.93	1.51	4.39	2.73	5.06	3.37
		D	0.94	0.68	2.75	1.85	5.57	3.23	8.05	3.98
	Millie	A	0.60	0.42	0.86	0.48	0.97	0.48	1.01	0.48
		B	0.77	0.28	1.10	0.38	1.24	0.46	1.29	0.49
		C	0.63	0.36	1.59	0.75	2.63	1.02	3.17	1.13
		D	1.15	0.30	3.58	0.76	7.66	1.22	10.85	1.70
	New-bonnet	A	0.42	0.20	0.68	0.32	0.85	0.41	0.93	0.45
		B	0.31	0.12	0.67	0.33	1.16	0.91	1.52	1.47
		C	0.48	0.30	1.27	0.76	2.42	1.35	3.49	2.04
		D	1.02	0.84	2.66	2.07	4.76	3.22	6.40	3.92

susceptible to temperature and/or RH even within equal EMC conditions.

As demonstrated in table 5, higher HMC rice had higher HRYR no matter how long the drying duration. Drying duration increased the HRYRs for high HMC rice more than for medium HMC rice. Therefore, HRYR of high HMC rice was more susceptible to drying duration than that of medium HMC rice.

Of the four varieties, Lacassine had the highest HRYRs, and Newbonnet had the lowest (table 5). Alan was slightly higher in HRYR than Millie, and both of them had HRYR values somewhere between the other two varieties.

The significance of the three interactions in table 5 indicated that the HRYR was sensitive to the coupled factors. Regarding the interaction of HMC and drying condition, for the high HMC rice, HRYR increased from drying condition A to D; whereas, for the medium HMC rice, HRYR was generally greatest at condition D and lowest at condition B. HRYR increased with duration for both high and medium HMC.

Relations Between Drying Rate Constant k and HRYR

Figure 4 shows the relation between HRYR and drying rate constant k, where the four points of each curve represent the k and HRYR values averaged across all experimental data at four drying conditions at a given drying duration. In general, HRYR increased with k. Drying at a higher k value caused more rapid moisture movement from the kernel, a higher moisture gradient inside the kernel, and consequently more HRYR. Figure 4 shows that there was less change in HRYR as k increased more for the 30 min drying duration than for the longer durations. Also, the amount of HRYR at a given k value increased with drying duration.

To establish a model for describing the relationship between HRYR and k, an empirical exponential equation was used to fit the data by means of the NLIN procedure from SAS:

$$HRYR = \gamma_0 \times \exp(\gamma_1 \times k) \quad (4)$$

where γ_0 and γ_1 were time dependent dimensionless parameters. Each curve in figure 4 corresponded to one pair of γ_0 and γ_1 values. By fitting the HRYR-k curve of each of the eight drying durations, the value of γ_0 and γ_1 for each drying duration were obtained. γ_0 and γ_1 were then plotted against drying duration as illustrated in figures 5 and 6. γ_0 decreased while γ_1 increased with drying

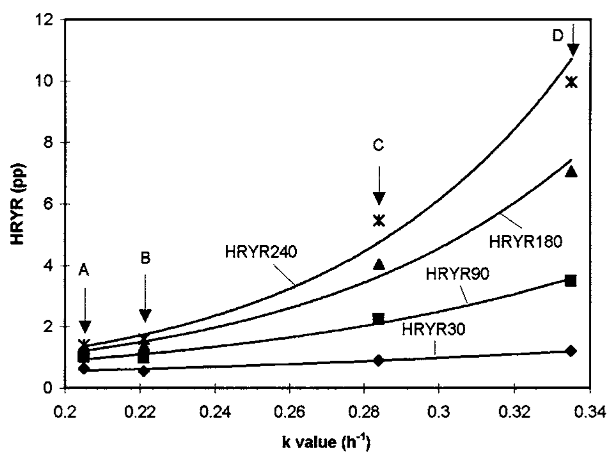

Figure 4–Head rice yield reduction (HRYR) expressed as percentage points (pp) and drying rate constant (k value) averaged across all experimental data at the four drying conditions (A, B, C, and D as defined in fig. 1) for drying durations of 30, 90, 180, and 240 min.

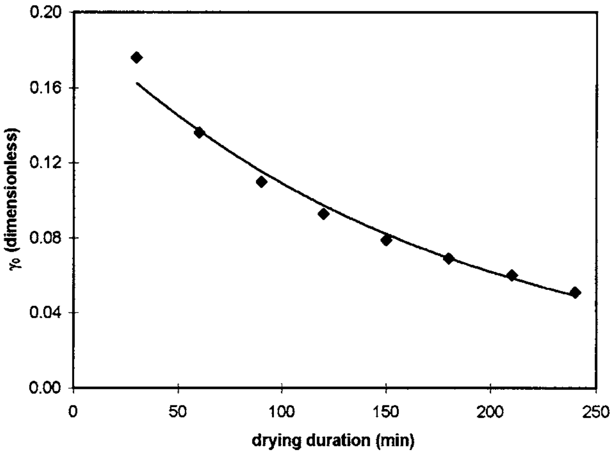

Figure 5–Relation of γ_0 vs drying duration (data points represent constant values in equation 4 fitted from experimental data, and the curve represents equation 5).

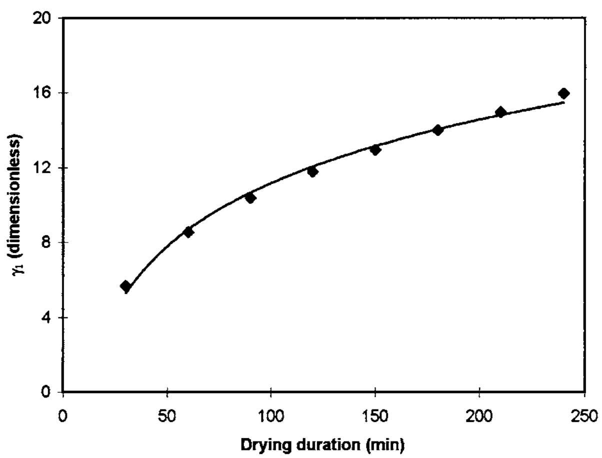

Figure 6–Relation of γ_1 vs drying duration (data points represent constant values in equation 4 fitted from experimental data, and the curve represents equation 6).

duration. Further curve fitting using the NLIN procedure from SAS yielded the following:

$$\gamma_0 = 0.193 \times \exp(-0.341 \times t) \quad (5)$$

$$\gamma_1 = 8.694 + 4.882 \times \ln(t) \quad (6)$$

where t is in h. Equation 4 can then be expressed by substituting equations 5 and 6 into equation 4 as:

$$\text{HRYR} = 0.193 \times \exp(-0.341 \times t + [8.694 + 4.882 \times \ln(t)] \times k) \quad (7)$$

By means of this model, HRYR can be estimated in terms of the drying rate constant and drying duration. Conversely, the k value and corresponding drying duration can be determined to control the HRYR within a certain limit. At four HRYR levels (2, 4, 6, and 8 pp), profiles of k values versus drying duration were generated using equation 7 and are shown in figure 7. As expected, higher HRYR was produced either by higher k values at a certain

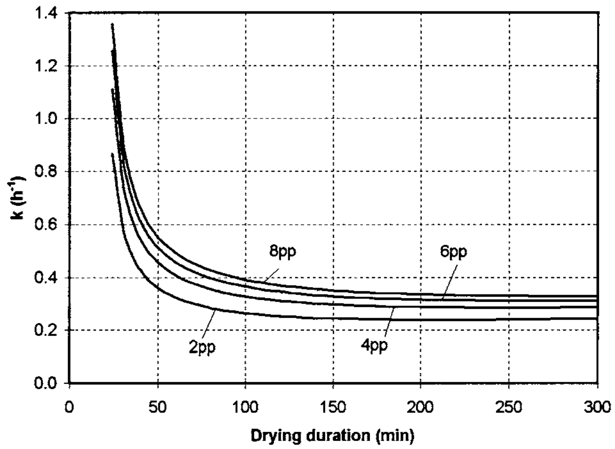

Figure 7–Relation between k values and drying duration (eq. 7) at 2, 4, 6, and 8 percentage points (pp) of HRYR levels.

drying duration, or by longer drying durations at a certain k value. To maintain a constant HRYR, drying duration should decrease with increasing k values. The figure may be used as a guide for proper selection of k value and/or drying duration. For example, for a fixed drying duration, say, 150 min, the k value should be no more than 0.243 h^{-1} to maintain HRYR under 2 pp, 0.297 h^{-1} under 4 pp, and so on. Values of k can be maintained at these levels by controlling drying conditions. Alternatively, at a given drying condition with a k value of, say, 0.5 h^{-1}, drying duration cannot exceed 35 min to maintain HRYR under 2 pp, 45 min under 4 pp, and so on. At a k value of 0.23 h^{-1}, HRYR can be controlled under 2 pp, regardless of the drying duration.

It should be mentioned that equation 7 is based on averages of the experimental data across the four drying conditions used. As concluded earlier, k and HRYR were also influenced by other factors such as variety, HMC, etc. The relationship between k and HRYR caused by other factors may differ from that caused by the drying condition. Consequently, models concerning the relation of k versus HRYR might be different owing to these factors. Further experiments should be conducted to quantify the k values as a function of drying air temperature and RH.

Conclusions

Experimental drying data representing six variety/harvest MC combinations, four drying conditions, two storage times prior to drying, and two repetitions were fitted using a Newton's equation to derive the drying rate constant k for each drying curve. Statistical analysis showed that the k value was significantly influenced by drying condition and variety as well as the interaction of drying condition×storage. Drying conditions C and D, selected to correspond to a theoretical EMC of 6.8%, produced higher k values than drying conditions A and B corresponding to an EMC of 9.5%. Of the four varieties, Alan was found to have the highest k values and Newbonnet the lowest.

Experimental HRYR data were fitted to a model used by Banaszek and Siebenmorgen (1990). By means of this model, HRYRs at various drying durations were calculated. HRYR was found to be significantly influenced by drying condition, variety, and HMC, as well as the interactions of drying condition with HMC, variety, and storage. Greater HRYRs were associated with increased drying durations. HRYRs were higher with high HMC, drying conditions C and D, and variety Lacassine.

The relationship between k and HRYR was quantified. HRYR increased with k value, and this increase was pronounced with greater drying duration. An empirical model of HRYR was produced as a function of the drying rate constant k and drying duration t. By means of this model, drying conditions and drying duration can be properly controlled to limit the HRYR within allowable levels. However, because the model (eq. 7) was developed based on limited experimental data, further experimentation is required to validate the general applicability of the model.

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