Moisture Adsorption Rates of Rough Rice

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Abstract

The rate at which moisture was adsorbed by rough rice was determined at various levels of temperature, relative humidity and initial moisture content. Air temperatures of 12.5, 20, and 30° C, relative humidities of 70 and 90%, and initial moisture contents ranging from approximately 9 to 15% wet basis were used to obtain moisture content data over time. At least 70% of the adsorption occurred within the first 24 hours of exposure to the humid environments. The rate of moisture adsorption increased with increasing temperature and relative humidity levels and decreased with increasing initial moisture content and time from onset of exposure to the airstream. Thin-layer adsorption equations were developed to predict moisture content with respect to time for the conditions used in this study. The values predicted with the developed equations agreed closely with the experimental data.

Introduction

Moisture adsorption occurs when the vapor pressure within kernels is lower than the vapor pressure of the surrounding air. Kunze and Prasad (1978) have shown that moisture adsorbing environments can exist in the field before harvesting and subsequently during harvesting, holding, transport, drying and storage. Kunze (1988) states that when rice in the field reaches 30% moisture or below, there already may be grains with sufficiently low moistures that fissure when they readsorb moisture. The lower the moisture content (MC) of the rice in the field, the higher in general is the percentage of fissured grains. Kernels can fissure in the field by first drying during the day and then rapidly readsorbing moisture during the evening or night. Lague and Jenkins (1989) developed a finite element model which simulates heat transfer, moisture transport, and internal expansion/contraction of rice kernels. Under field conditions, the model predicted fissuring of the grain during rewetting periods only when the liquid diffusivity of the hull and bran layers was increased to allow moisture to penetrate into the endosperm during rewetting phases.

Moisture adsorption is an important concern when developing models simulating deep bed drying and aeration of grain. Equations are needed to predict changes in the MC of thin layers of grain as a function of time as the layers are exposed to given air conditions. Limited work has been done in developing thin-layer rewetting equations for rough rice; however, considerably more work has been conducted for other grains. Extensive contributions to a better understanding of moisture adsorption by corn have been made by Rugumayo (1978). Misra (1978) developed an empirical thin-layer wetting model by supplementing his own data with that determined in wetting tests by Chittenden (1961) and Rugumayo (1978). The developed model used an equilibrium moisture content (EMC) equation developed by Bakker-Arkema et al. (1974). Misra determined that among the independent variables, air temperature and initial corn MC were the most significant in affecting the wetting parameter. In modeling thin-layer adsorption in soybeans, Osborn et al. (1988) found temperature and relative humidity (RH) to be significant factors, but also found initial moisture content (IMC) in the range of 9 to 14% dry basis to be non-significant. Krueger and Bunn (1988) incorporated wetting calculations as a subroutine in Thompson's (1972) cross-flow drying model to better predict the drying and aeration processes in corn. Steffe and Singh (1980) used mathematical equations based on Fick's law to model the thin-layer drying of white, brown and rough rice. Although no equations were developed, Karon and Adams (1949) and Breese (1955) presented moisture adsorption and desorption curves for rough rice using static conditions.

Much research has been conducted to develop thin-layer drying equations and to better understand the desorption phenomenon in rice and the effects on head rice yield (HRY). Far less research has been devoted to developing thin-layer adsorption equations and to determining the rate at which moisture adsorption affects head rice yields. The comparisons of several rewetting equations that were tested for modeling data from a series of moisture adsorption tests are reported in this article. HRY data associated with these tests as well as the relationship of moisture adsorption rates to HRY reduction are given in Banaszek and Siebenmorgen (1990a).

Objectives

The objectives of this research were to:

- Measure the rate of moisture adsorption by rough rice as influenced by IMC (ranging from 9 to 15%*) subjected to an airstream at various temperatures and RHs; and

*Unless otherwise specified, all references to moisture content are on a wet basis.

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- Develop a rewetting equation, based on the experimental data, to predict the MC of rough rice exposed to adsorptive conditions.

Materials and Methods

Newbonnet rice, a long-grain variety, was harvested at the Rice Research and Extension Center, Stuttgart, Arkansas, at approximately 20% MC during September 1987 and stored at 1° C for 6 months. The rice was dried in a chamber supplied with air at approximately 20° C with RH set at the desired level according to the Modified Henderson Equation (ASAE, 1987) to attain nominal MCs of 9.0, 10.5, 12.0, 13.5, and 15.0%. All reported MCs are the average of at least three readings given by a Motomco 919A† moisture meter. After drying, all rice was placed in plastic bags and stored at 1° C until testing.

Rice was caused to adsorb moisture by placing 450-g samples in trays in a conditioning chamber (fig. 1). The chamber was built to accommodate sixteen, 152 × 254 mm (6 × 10 in.) trays with perforated bottoms placed in parallel above an air plenum. The trays were 150 mm deep with the rice layer being approximately 15 mm thick. Air was supplied to the plenum by a RH and temperature control unit (Parameter Generation and Control 300 CFM Climate-Lab-AA). According to manufacturer's specifications, this unit is capable of maintaining RH within ±0.5% and dry-bulb temperature within ±0.2° C. In addition to the monitoring equipment of the control unit, a RH and temperature monitoring system (Phys-Chemical, Humitemp model B) was used to monitor the air conditions in the plenum below the samples. The readings between the two air condition monitoring systems were in close agreement and indicated the control unit performed within manufacturer's specifications. After air passed through the samples, it was returned to the control unit to form a closed loop system. The total airflow rate was 26.4 L/s (56 cfm) or 1.65 L/s (3.5 cfm) per tray.

Experimental Procedure

The experimental design for this study consisted of rewetting rough rice from the approximate MC levels of 9.0, 10.5, 12.0, 13.5, and 15.0% using an airstream at temperatures of 12.5, 20, and 30° C and RHs of 70 and 90%. For each test condition, sufficient rice from one of the five MC lots was removed from storage to load 12 conditioning unit trays. After removal from storage and prior to conditioning, the rice was placed in ziplock plastic bags and allowed to equilibrate to room temperature of approximately 20° C. Immediately prior to exposure to conditioned air, sample MCs were measured to determine the exact IMC.

The control unit was allowed to reach steady-state operation at a given temperature/RH combination prior to loading samples. The 12 samples were loaded into the conditioning unit with each of the four remaining trays filled with 450 g of "filler" rice. An additional sample was selected to represent the control (time = 0 h). Samples were removed from the conditioning chamber at time intervals of 1, 2, 4, 8, 16, 24, 48, 72, 96, 120, 144, and 168 h from the onset of exposure to the conditioned air. The samples were immediately double-bagged in zip-lock plastic bags, placed in cold storage, and MCs determined after at least one week in storage. This storage duration was assumed adequate to allow all kernels to fully equilibrate from the kernel surface to the interior. After samples were removed from the conditioning unit, filler rice was placed in the trays to maintain a uniform airflow rate through all trays.

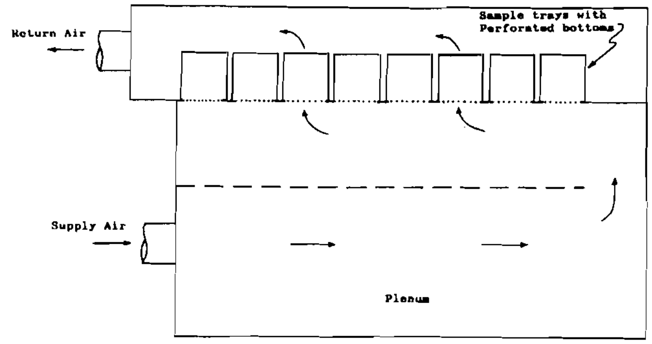

Figure 1–Conditioning chamber with air supplied from Parameter Generation and Control unit.

Results and Discussion

Adsorption Tests

The moisture adsorption data for rice exposed to airstreams at the various temperature and RH combinations used in this study are shown in figures 2 through 6. The curves were drawn using an equation described below. For some of the temperature/RH/IMC combinations, the airstream was not moist enough to cause adsorption by the rice. Only those combinations in which moisture adsorption occurred are presented. Thus, for many of the temperature/RH conditions, only curves associated with the lower IMCs are shown. Further, the temperature/RH combination of 12.5° C/90% RH was not obtainable with the control units in the ambient conditions in which they were located.

In general, figures 2 through 6 show that the moisture adsorption curves for the various IMCs followed similar patterns. With all IMCs, most of the adsorption occurred within the first 24 h. Figure 2, displaying the moisture adsorption curves for 30° C and 90% RH, indicates that MC increased dramatically during the early stages of

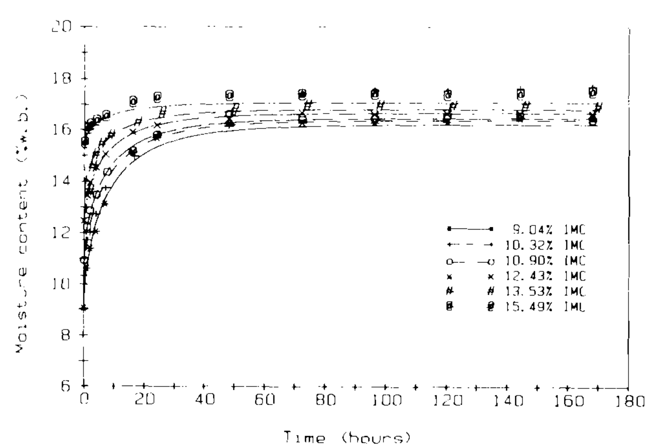

Figure 2–Experimental data and predicted moisture adsorption curves for rough rice exposed to an airstream at 30° C and 90% RH.

†Mention of a commercial name does not imply endorsement by the University of Arkansas.

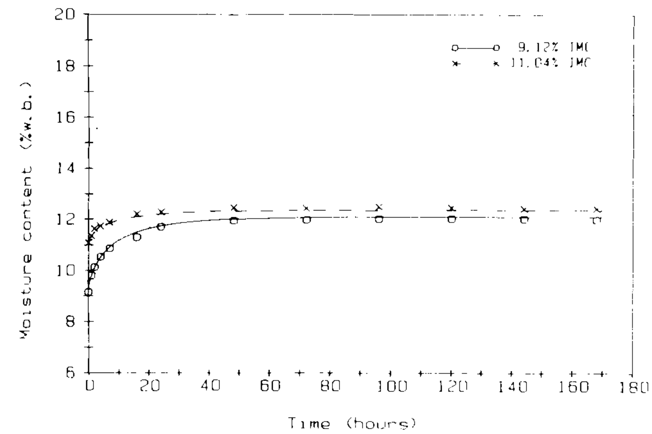

Figure 3–Experimental data and predicted moisture adsorption curves for rough rice exposed to an airstream at 30° C and 70% RH.

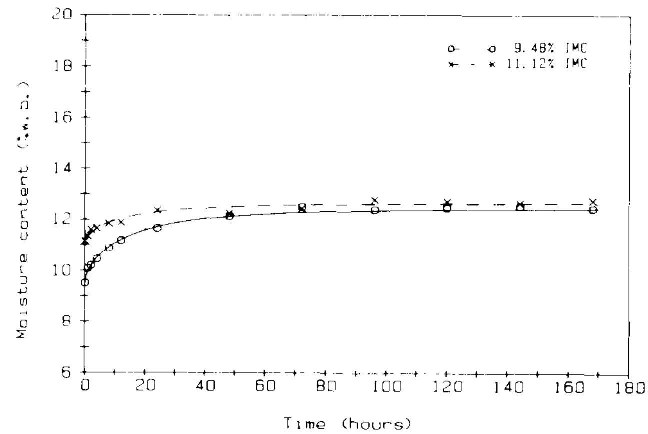

Figure 5–Experimental data and predicted moisture adsorption curves for rough rice exposed to an airstream at 20° C and 70% RH.

moisture adsorption. Over 89% of the moisture which was adsorbed took place within the first 24 h for all IMCs at this air condition. This observation is consistent with that of Sokansanj et al. (1985) who reported that equilibrium conditions for canola were reached within 12 to 24 h using an equilibrium RH method to determine equilibrium moisture content (EMC).

Figure 3 displays the response of rice at 9 and 11% IMC to air at 30° C and 70% RH. The response was similar to the conditions of figure 2 with approximately 90% of the adsorption having taken place in the first 24 h. The response of rice to 20° C and 90% RH is shown in figure 4. The curves show that the rate of moisture adsorption was less than that at 30° C and 90% RH. At 24 h, approximately 70% of the maximum amount of moisture adsorption had occurred; whereas, 89% had occurred in the 30°C case. Thus, at the 90% RH condition, temperature appears to have had a significant effect on the rate of adsorption. However, comparison of figure 3 (30° C/70% RH), figure 5 (20° C/70% RH) and figure 6 (12.5° C/70% RH) shows that temperature had less effect on the rate of adsorption at the 70% RH level.

An important observation found early in the study was that the curves for a given air condition in figures 2 through 6 did not reach a single asymptotic EMC value. In other words, for a given air condition, each IMC level resulted in a different EMC value. This phenomenon was partially explained by Harper (1976) who states that "most solid foods undergo irreversible changes during drying, so that an EMC approached by adsorption is actually for a different material." Thus, it is hypothesized that irreversible changes occurred when the rough rice was dried to the various IMC levels which resulted in the rice at each level of IMC acting as different materials with each having its own EMC. Banaszek and Siebenmorgen (1990b) investigated the relationship between IMC and EMC for adsorptive conditions and found the following equation relating IMC to EMC:

$$\mathrm{EMC} = a_1 * \mathrm{IMC} + b_1 * \mathrm{RH} + c_1 * T + d_1 \qquad (1)$$

where

EMC	=	equilibrium moisture content, % wet basis,
IMC	=	initial moisture content, % wet basis,
RH	=	relative humidity, decimal,
T	=	temperature, ° C,
a_1,b_1,c_1,d_1	=	regression coefficients, Table 1.

Rewetting Equations

In an effort to model the moisture transfer to rice with respect to time, several forms of the moisture diffusion

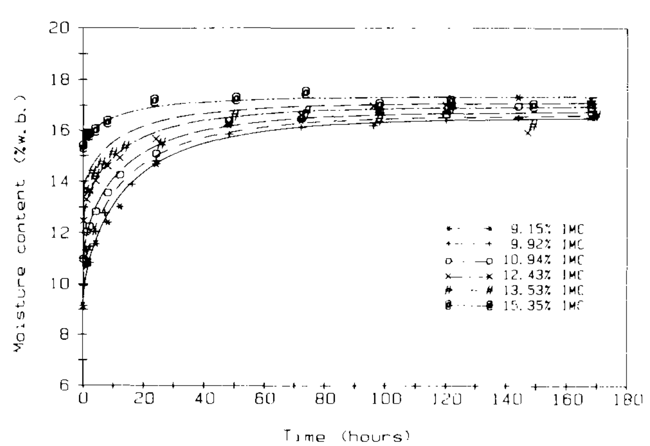

Figure 4–Experimental data and predicted moisture adsorption curves for rough rice exposed to an airstream at 20° C and 90% RH.

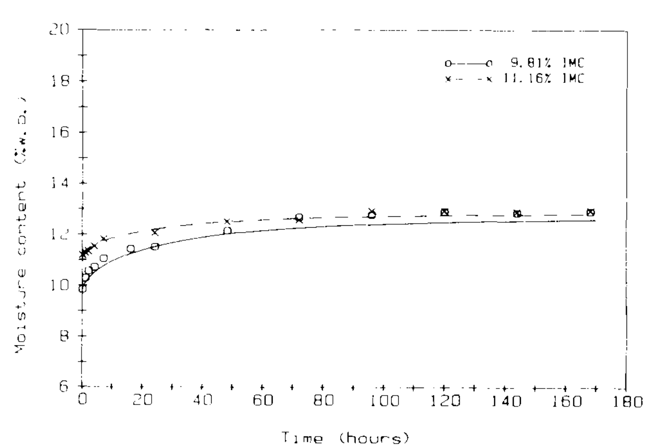

Figure 6–Experimental data and predicted moisture adsorption curves for rough rice exposed to an airstream at 12.5° C and 70% RH.

TABLE 1. Regression coefficients and statistics for equilibrium moisture content equation (equation 1)

Equation 1: $EMC = a_1 * IMC + b_1 * RH + c_1 * T + d_1$

Coefficients	Standard error of estimates	Model
a_1 = 0.12669489	$s(a_1)$ = 0.01512453	MSE = 0.035
b_1 = 20.63328109	$s(b_1)$ = 0.31499144	
c_1 = − 0.02979736	$s(c_1)$ = 0.00418886	R^2 = 0.9916
d_1 = − 2.58879359	$s(d_1)$ = 0.26488243	

equation (Henderson and Perry, 1976) were analyzed. The forms tested were as follows:

$$MR = \exp(-k * t) \tag{2}$$

$$MR = a * \exp(-k * t) \tag{3}$$

$$MR = \exp(-k * t^n) \tag{4}$$

$$MR = a * \exp(-k * t^n) \tag{5}$$

where
- MR = (Mt–Me)/(Mo–Me), moisture ratio, dimensionless,
- Mt = moisture content at time t, % wet basis,
- Me = equilibrium moisture content (EMC), % wet basis,
- Mo = initial moisture content (IMC), % wet basis
- t = time, h,
- a,k,n = regression coefficients.

These equations were chosen based on reported models describing rewetting characteristics of other grains. Davis and Henry (1988) used the form of equation 2 to model moisture regain in tobacco leaf. Many investigators (Misra and Brooker, 1980; Osborn et al., 1988; Shatadal et al., 1989) have successfully used the form of Page's (1949) equation (eq. 4) to mathematically describe the thin layer rewetting rate of various cereal grains and oilseeds. Equations 3 and 5, which are modifications of equations 2 and 4, were included to test whether the coefficient 'a' was equal to a value other than one.

Equations 2 through 5 require inputs for EMC (Me) to predict moisture content with respect to time. In order to eliminate the necessity of approximating EMC for each adsorption curve, equation 1 was used to determine EMC for each IMC/RH/T combination for use in these equations.

The NLIN least squares procedure from SAS (1987) was used to fit equations 2 through 5 to each adsorption curve. As such, applicable regression coefficients were determined by NLIN for each adsorption curve. The coefficients obtained were evaluated using GLM procedure (SAS, 1987) to determine if there were significant differences between curves. The parameter 'k' was the only parameter found to be significantly different between curves at a significance level of 5% for each of the equations 2 through 5. Since the parameters 'a' and 'n' were not found to be significantly different between curves, the respective values of these parameters for all curves were then averaged. After fixing the 'a' and 'n' parameters at their resulting average value, NLIN was again used to calculate new values for the 'k' parameter.

The next step was to develop a mathematical relationship between IMC, RH, and temperature to predict values for the 'k' parameter in equations 2 through 5. The REG least squares regression procedure (SAS, 1987) was used to fit the 'k' values to an equation of the form:

$$k_i = e_i * IMC + f_i * RH + g_i * T + h_i \tag{6}$$

where
- k_i = regression coefficient for equations i = 2 through 5,
- IMC = initial moisture content, % wet basis,
- RH = relative humidity, decimal,
- T = temperature, ° C,
- e_i, f_i, g_i, h_i = regression coefficients.

A stepwise approach was used in this procedure which allowed testing the validity of including each of the variables as a component of a model predicting 'k'. All variables except RH were significant in predicting 'k' for equations 2 through 5 at a significance level of 5%. Although RH was found to be nonsignificant in the 'k' parameter, it was highly significant in determining EMC (eq. 1) and is, thus, a significant factor in modeling the rate of adsorption.

Using the form of the equation for 'k' given in equation 6, the NLIN least squares procedure from SAS was again used to fit equations 2 through 5 to the entire, pooled data set. The resulting error mean square (MSE) for equations 2 through 5 were 0.0100, 0.0083, 0.0068, and 0.0068, respectively. Based on these results, it appears that equations 4 and 5 are better overall predictors for moisture adsorption with respect to time. Equation 4 was selected as the better choice as compared to equation 5 due to its simpler form. The choice of equation 4 is also consistent with that of previous research (Page, 1949; Misra and Brooker, 1980; Osborn et al., 1988; Shatadal et al., 1989). The regression coefficients and pertinent statistics for equation 4 are presented in Table 2. Equations 2 through 5 are also presented in Table 2 with their respective MSE.

Rate of Adsorption

Equation 4 can be rearranged to better represent MC as a function of time in the following form:

TABLE 2. Moisture ratio equations 2 through 5 and pertinent regression coefficients and statistics

Equation 2:	$MR = \exp(-k_2 * t)$	MSE = 0.0100
where:	$k_2 = e_2 * IMC + g_2 * T + h_2$	
Equation 3:	$MR = a_3 * \exp(-k_3 * t)$	MSE = 0.0083
where:	$k_3 = e_3 * IMC + g_3 * T + h_3$	
Equation 4:	$MR = \exp(-k_4 * t^{n_4})$	MSE = 0.0068
where:	$k_4 = e_4 * IMC + g_4 * T + h_4$	
n_4 =	0.6792473107	(average value for all conditions)
e_4 =	0.0038177150	$s(e_4)$ = 0.00271576028
g_4 =	0.0081850498	$s(g_4)$ = 0.00072367082
h_4 =	− 0.0389231415	$s(h_4)$ = 0.03026871181
Equation 5:	$MR = a_5 * \exp(-k_5 * t^{n_5})$	MSE = 0.0068
where:	$k_5 = e_5 * IMC + g_5 * T + h_5$	

$$Mt = (Mo - Me) * \exp\left(-k * t^{n}\right) + Me \qquad (7)$$

Equation 7 was used to generate the curves in figures 2 through 6. The curves fit the data well for all air conditions and IMC levels as evidenced by an overall MSE value of 0.0068.

The rate of adsorption (change in Mt with respect to a change in time) is represented by the partial derivative of Mt with respect to time:

$$\frac{d(Mt)}{d(t)} = (Mo - Me) * \exp\left(-k * t^{n}\right) * \left(-k * n * t^{n-1}\right) \qquad (8)$$

Rate of adsorption curves were generated using eq. 8 and are shown in figures 7 through 9. Figure 7 displays the adsorption rates for varying levels of IMC at the condition of 30° C and 90% RH. As was expected, the lowest IMCs produced the highest adsorption rates resulting from greater differences between IMC and EMC at low IMCs than at high IMCs. At this air condition, the rate of adsorption declined rapidly in the zero- to five-hour time range. All IMC levels had reached a low rate (less than 0.1 % MC per h) within 24 h and approached equilibrium (adsorption rate near zero) at approximately 48 hours. These adsorption rates generally agree with those presented by Osborn et al. (1988) for soybeans and Shatadal et al. (1989) for canola.

Figure 8 shows the effect that temperature has on adsorption rates at a base condition of 9% IMC and 90% RH. The curves indicate that the rate of adsorption was initially directly proportional to temperature. This agrees with the Simmonds et al. (1953) findings in which moisture transfer was accelerated by increasing temperature. After about nine hours of exposure time, the 20° C and 30° C curves crossed each other. The initially higher adsorption rates for the 30° C curve coupled with a lower EMC at 30° C than at 20° C for a given RH resulted in the rice approaching equilibrium before the 20° C curve which had an initially slower rate of adsorption. Thus, while the 30° C curve was nearing equilibrium, equilibration of the 20° C curve lagged slightly behind which resulted in a slightly higher adsorption rate after nine hours of exposure. The same process occurred when the 12.5° C curve crossed the 30° C curve at 12 hours of exposure time and also when the 12.5°C curve crossed the 20° C at 18 hours of exposure.

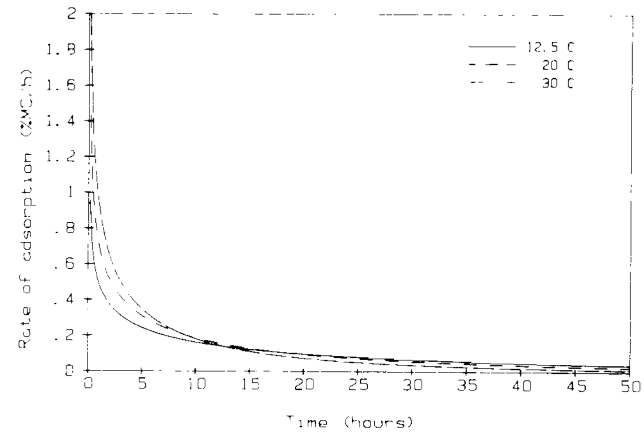

Figure 8–Adsorption rates as affected by temperature at the condition of 9% IMC and 90% RH.

Figure 9 shows the effects that RH has on adsorption rates at a base condition of 9% IMC and 30° C. The 90% RH curve produced the higher adsorption rates compared to the 70% RH curve. The rates at the 90% RH level were consistently at least twice as high as those of the 70% RH level.

SUMMARY AND CONCLUSIONS

Adsorption curves at initial moisture contents varying from 9 to 15% were experimentally obtained to show the effects of relative humidity, temperature, and initial moisture content on adsorption characteristics of rough rice. The data show that with the airflow used in this study, most of the adsorption took place in the first 24 h of exposure.

Several equations typically used to model moisture transfer in grains were evaluated for use in describing moisture content as a function of time, initial moisture content, air temperature and relative humidity. Page's equation (eq. 4) described the rewetting of rough rice quite well for the adsorptive conditions of this study. The 'k' parameter of Page's equation was found to be a function of initial moisture content and temperature, while the 'n' parameter was determined to be a constant. Relative humidity was found to be a non-significant variable in the

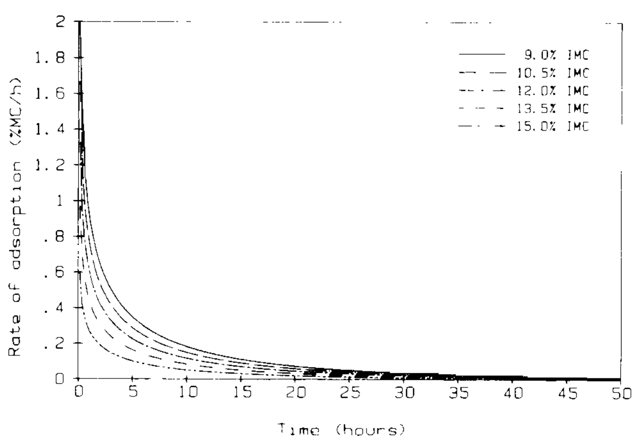

Figure 7–Adsorption rates as affected by initial moisture content at the condition of 30° C and 90% RH.

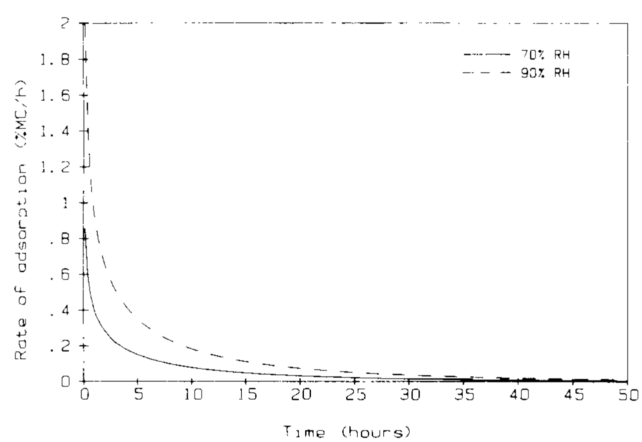

Figure 9–Adsorption rates as affected by relative humidity at the condition of 9% IMC and 30° C.

'k' parameter but was highly significant in determining equilibrium moisture content.

Adsorption rates were directly related to temperature in that higher rates were associated with higher temperatures until approximately 13 hours of exposure. After 13 hours of exposure, the adsorption rates were higher for lower temperatures. Adsorption rates were consistently twice as high at the 90% RH level as compared to the 70% RH level at a base condition of 9% IMC and 30° C air temperature. Increasing the IMC level correspondingly decreased the adsorption rates at all conditions.

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