MOISTURE SORPTION OF BAGGED GRAIN STORED UNDER TROPICAL CONDITIONS

by

PURBOYO GURITNO

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Approved by :

Do Sup Chung

Ekramul Haque

Co - Major Professors

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I. INTRODUCTION

Cereal grain is hygroscopic. It gains or loses moisture depending upon the surrounding environmental conditions. When the ambient air is more humid than the grain, the grain gains moisture. Conversely, when the air is drier than the grain, the grain loses moisture (Brooker et al., 1974; Henderson and Perry, 1976). Bagged grain stored in warehouses in tropical countries behaves in the same manner.

About ten percent of the grain produced on the farm never reaches the market. This loss occurs in the field and during storage (Hall, 1970). The rate of storage losses and deterioration depends on physical and biological factors, and the storage environment (Anon, 1978). Physical factors which contribute to storage losses are caused by processes before the storage, such as harvesting, threshing, shelling, and drying. Insects, mites, fungi, and rodents are the principal biological factors of deterioration during grain storage. Insects and other pests are a bigger problem in regions where the relative humidity and temperature are high. At low temperatures and/or low relative humidity, conditions are generally not as favorable for insect and fungal growth. High temperature and high relative humidity, on the other hand, encourage mold formation and provide conditions for rapid growth of insect populations (Christensen and Sauer, 1982). Water activity, defined as the percentage relative humidity expressed as a decimal at a particular product temperature is an important variable for most of the microbial degradation processes of food products (Erickson, 1982).

Grain moisture is possibly the most important factor responsible for causing storage losses. At lower moisture content insects, fungi, and other pests can not proliferate as easily as in a high moisture environment. The maximum moisture for safe storage for a year varies from 12 % (Sorenson and Davis, 1953), to 13 % (Esmay et al., 1979), to 14 % (Zin, 1989; Anon, 1950; Wahab and Yon, 1980). Another way of determining safe storage is by the use of relative humidity. The equilibrium relative humidity at 13.0 % moisture content ranges from 65 to 75 percent at temperature between 10 to 30 ^{o}C (50 to 86 ^{o}F). The safe storage moisture content for products such as cereal grains is usually accepted as that in equilibrium with 70 % relative humidity (Pixton and Warburton, 1971). At 70 % relative humidity the shelled corn will be in equilibrium with about 14 % moisture content (Thompson and Shedd, 1954).

Warm and humid conditions of tropics create serious grain storage problems. Humid tropical areas are characterized by relatively high temperature, ranging from 21 to 35 °C (70 to 95 °F), and high relative humidities ranging 75 to 80% or higher (Kanujoso, 1987). In tropical countries it is not only difficult to dry the grain to a safe storage moisture level, it is also difficult to keep the dry grain from adsorbing moisture during storage. The shelled corn stored at an initial moisture content of 13 %, will eventually rise to about 18 % moisture if the storage environment is at 26.7 °C (80 °F) and 80 % relative humidity. The grain at 16 % moisture level becomes more susceptible to insect, mold, and other pest damage (Brooker et al., 1974; Hall, 1980).

Success in maintaining quality of the grain in the storage depends mainly upon how well the grain are managed during storage. A proper grain storage practice is to maintain conditions in the grain that will keep and preserve its processing and marketing values at as high a level as possible.

Off-farm storage in tropics usually consists of piling of bagged grain up to 20 layer high in warehouses. Polypropylene and jute or gunny bags are frequently used (Acasio et al., 1982; Isbagijo and Sumardi, 1978; Mendosa et al., 1982). Bag storage is used because bags are readily avalaible and cheap. The handling of bagged grain does not require a high level of technology (Anon, 1978). The bag material offers some resistance to the moisture movement to the grain in bags. A frequent question asked in the humid countries is : which is a better barrier to moisture adsorption, a jute or a polypropylene bag ?.

Available data to explain the moisture transfer phenomenon in bagged grain is extremely limited. The objectives of this research were :

1. To determine the rate of moisture sorption of grains in bags under various environmental conditions;
2. To explain the moisture sorption by the use of accepted moisture sorption models;
3. To assess the difference in moisture sorption rate due to the fiber from which the bag is woven (e.g. jute bag vs polypropylene bag).

II. REVIEW OF LITERATURE

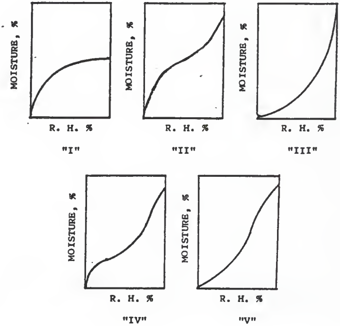
2.1. General Concept of Moisture Sorption in Cereal Grains.

A fundamental characteristic of biological materials, which influences virtually every aspect of handling, storage, processing and consumption of food products, is their basic hygroscopicity. That is, when these products are exposed to water vapor of a definite pressure, sorption of the vapor by the product will occur. During the storage the hygroscopic material such as, shelled corn and rough rice, gain or lose moisture when the water vapor pressure in the surrounding air is more or less than the water vapor pressure within the particle. The gain of moisture in the product is called adsorption and the loss is called desorption (Brooker et al., 1974; Dunstan et al., 1973; Ngoddy and Bakker-Arkema, 1972). The amount of water adsorbed or desorbed depends on the water vapor pressure within the particle and in the air surrounding the product, the product and air temperatures, and product characteristics (Ngoddy and Bakker-Arkema, 1972).

It is customary to divide the sorption process into two catagories, namely physical sorption, also termed Van der Waal sorption, and chemisorption or activated sorption. Chemisorption involves transfer of electron between the solid (adsorbent) and the gas (adsorbate) (Young and

Crowell, 1962). Physical sorption is caused by intermolecular forces between molecules of water vapor and the surface of adsorbent (polar site of the adsorbent) In general, polar molecules such as H_2O, NH_3, and alcohol, or molecule possessing the following polar groups: $-NH_2$, -NH-, -OH, -COOH-, $-COONH_2$, etc., are considered to be sorptive sites on the adsorbent since the positive and negative charges in the above molecules are not symmetrically distributed (Chung and Pfost, 1967).

The amount of vapor adsorbed per amount of adsorbent is a function of pressure P, the temperature T, and also the nature of the adsorbate and the adsorbent. The plot between the amount of vapor adsorbed or desorbed and the vapor pressure of a given solid at a constant temperature is called the sorption isotherm. If the grain is made to adsorb moisture, the plot is called adsorption isotherm, and if the grain desorbs moisture, it is called desorption isotherm. The sorption isotherm is used to present the relationship between equilibrium moisture content and the relative humidity. The sorption isotherm can be classified into five types (Figure 1). The five types are : 1. The type I curve is Van der Waal sorption and is well known as the Langmuir sorption isotherm; 2. Type II is called the S-shaped or sigmoid curve; 3. Type III is closely related to type II since type II and III describe multimolecular sorption and they indicate that adsorption will increase indefinitely as the vapor pressure increases; and 4. Type IV and V relate to the sorption on a highly porous sorbent and the sorption increases asymptotically as the vapor pressure increases (Brunaeur, 1943).



R.H (Relative Humidity)

Figure 1. Types of Sorption Isotherm as Classified by Brunaeur (1943).

Most of the cereal grains fall in the type II category for both the desorptive and the adsorptive phases (Figure 2). Because of the characteristic shape, the curve has been called S - shaped or sigmoid isotherm. Its shape has been generally attributed to multimolecular sorption and is of considerable importance to cereal grains (Hall and Rodriguez - Arias, 1958). Babbit (1945) found that for wheat the sigmoid curve described the desorptive phase and the adsorptive phase was better described by the type I curve. On the other hand, Chung and Pfost (1967) showed that both adsorption and desorption isotherms of corn starch, hull, gluten, and germ at 25 and 50 ^{o}C were well described by type II curves. This was also confirmed by Day and Nelson (1965), and Hubbard et al. (1957).

When water vapor is adsorbed at the surface of the sorbent, a quantity of heat is released. The released heat is called heat of adsorption. When water vapor is desorbed , a quantity of heat termed as heat of desorption is taken up (Chung and Pfost, 1967; Dunstan et al., 1973). The heat of desorption at constant moisture content can be evaluated by using the following formula :

$$\Delta H_d = R \left(\frac{T_1 x T_2}{T_1 - T_2}\right) \ln \frac{P_2}{P_1}$$

where, ΔH_d = heat of desorption at constant moisture content (BTU/lb)

R = universal gas constant (BTU/lb mole ^oR)

T_1 = absolute temperature at condition 1 (^oR)

T_2 = absolute temperature at condition 2 (^oR)

P_1 = the equilibrium vapor pressure at T_1 (Psia)

P_2 = the equilibrium vapor pressure at T_2 (Psia).

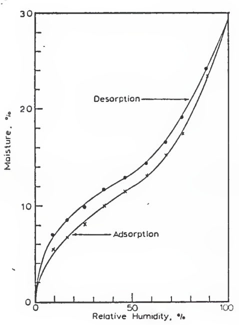


Figure 2. Adsorption and Desorption Isotherms of Shelled Corn at 22 ^oC (Chung and Pfost, 1967).

2.2. Equilibrium Moisture Content and Equilibrium Relative Humidity and Their Relationships.

Moisture sorption by stored grain is a dynamic process. The intergranular air temperature and relative humidity continuously change due to simultaneous heat and mass transfer between the ambient air and the grain until an equilibrium condition is reached. The moisture content of the grain at any time during this dynamic sorption process is a function of air temperature, relative humidity, and initial conditions of the grain.

The change in moisture content of grain may be an adsorption or desorption process depending upon whether water vapor is taken in or given off by the grain under the given environmental condition. The sorption rate of water vapor by cereal grain under environmental conditions to which it is exposed during storage and handling is of great commercial interest due to the influence of moisture content on the quality of stored grains. Moisture content of grain is one of the most important basic physico-chemical variables that affect the development of bacteria, mold, fungi, mites and insects (Christensen and Sauer, 1982; Sinha, 1973; Zeleny, 1954). Molds grow slowly, and some not at all below 10 ^{o}C (50 ^{o}F), but do serious damage at 29.4 ^{o}C (85 ^{o}F) if moisture conditions are favorable (Christensen and Sauer, 1982). Moisture of stored grains is an important factor in the life of insect pests since insects depend on grain as a food and water source to sustain life (Cotton and Wilbur, 1982).

The concept of equilibrium moisture content (E.M.C) is important for the drying, aeration, and storage. In order to determine the minimum moisture content to which grain can be dried under a given set of drying conditions (such as air temperature, and relative humidity), the E.M.C. of the grain is important (Brooker et al., 1974; Foster, 1982). The purposes of the aeration are to maintain a uniform temperature in the grain and to keep that temperature as low as possible (Foster and Tuite, 1982). At low and uniform temperature the moisture migration will not occur. By knowing the E.M.C of the grain, one can predict the aeration cooling time since there is a definite relationships between grain moisture, temperature, and the time to which grain can be held in storage before microorganism activities become serious problems (Foster and Tuite, 1982). The E.M.C of the grain can be used to determine whether stored grains will gain or lose the moisture. If the grain has an excessive gain in moisture, spoilage will occur. Knowing the E.M.C of the grain, one will be able to minimize storage problems (Dunstan et al., 1973; Hall, 1980).

The E.M.C is the moisture content reached by a hygroscopic product such as grain after the vapor pressure of water in the product has become equal to the water vapor pressure in the surrounding air. The relative humidity of the air surrounding cereal grain which is in equilibrium with the air is called equilibrium relative humidity (E.R.H) (Brooker et al., 1974). A product which attains its moisture equilibrium with the surroundings by gaining moisture is said to have reached the adsorption E.M.C. If the product reaches equilibrium by losing moisture, it is said to have reached the desorption E.M.C. Adsorption E.M.C. is smaller than desorption E.M.C., at a given E.R.H., the difference being termed as hysteresis (Brooker et al. 1974; Henderson and Perry, 1976). If the relative humidity of the surrounding air in contact with a product is higher than the E.R.H of the material at its current moisture content, the material will increase in moisture. Conversely, for an air relative humidity lower than the E.R.H, the moisture of the material will decrease (Henderson and Perry, 1976).

The equilibrium moisture relationship of the grain and the air has been the subject of many research studies, including those carried out by Henderson (1952), Chung and Pfost (1967), Strohman and Yoerger (1967), Gustafson and Hall (1974), Pfost et al. (1976), and Zuritz et al. (1979). A general review of the equilibrium moisture relationship in cereal grains was presented by Brooker et al. (1974) and Hall (1980).

Brooker et al. (1974) discussed five important equilibrium moisture content equations; namely the Brunauer, Emmett and Teller (B.E.T) equation, the Harkin- Jura equation, the Smith equation, the modified Henderson equation, and the Chung-Pfost equation. Some of the important equilibrium moisture equations are as follows :

2.2.1. The B.E.T Equation :

This theory was first developed in 1928 by Brunauer, Emmett and Teller and was based on the assumption that the same forces that produce condensation are responsible for the binding energy of multimolecular adsorption. The B.E.T equation constituted the first attempt to present a theory of physical adsorption. In general the B.E.T equation has been found to explain the sorption process for many adsorbents over the range of relative humidities between 5 to 35 percent, and some times to 50 percent. Outside of this range the equation usually fails. The equation is as follows :

$$V = V_m C P/(P_o - P)(1 + (C - 1)(P/P_o)$$

where, V = volume adsorbed

V_m = the volume adsorbed when the entire adsorbent is covered with monomolecular layer

P = the partial pressure of the vapor

P_o = the saturation pressure

C = constant.

The constant C can be defined by the following equation :

$$C = \frac{a_1 b_2}{b_1 a_2} (E_1 - E_L)/RT$$

where, a_1, a_2, b_1, b_2 = constant

$E_1 - E_L$ = net heat of adsorption of the first layer

R = the universal gas constant

T = absolute temperature.

The B.E.T equation is satisfactory for relative humidities below 43 percent.

2.2.2. Smith Equation :

Smith (1947) postulated the following equation to fit the isotherm of polymer.

$$V = f - g \ln(1 - P/P_o)$$

where, V = moisture content, dry basis

f and g = experimentally determined constant which depend on temperature

P/P_o = equilibrium relative humidity.

Smith equation holds for cereal grains subjected to the relative humidity range 50 to 95 percent (Becker and Sallans, 1956).

2.2.3. Chung-Pfost Equation (1967) :

This equation was applicable to a wide range of relative humidity and successfully tested for corn and their products. The equation is as follow :

$$\ln P/P_o = - A/RT \exp(-BM)$$

where P/P_o = equilibrium relative humidity (decimal)

A and B = constants

T = absolute temperature (^oR)

R = universal gas constant

M = equilibrium moisture content (decimal, dry basis).

2.2.4 Modified Chung-Pfost Equation :

The original Chung-Pfost equation was modified to cover other grains also. The equation is as follow (Pfost et al. 1976) :

$$M = E - F * \ln [- (T + C) * \ln (RH)]$$

where M = grain moisture, decimal dry basis

RH = relative humidity

T = temperature, ^oC

E, F, and C = constants.

2.2.5. Henderson's Equation (1952) :

This equation is applicable for lower ranges of humidity compared with Chung and Pfost equation. The equation is :

$$1 - P/P_o = \exp(- k\ T\ M^n)$$

where P/P_o = equilibrium relative humidity

T = absolute temperature (^oR)

M = equilibrium moisture content (decimal, dry basis)

k and n = constants.

Five E.M.C models having three or four constants in each equation; namely, the Henderson-Thompson (modified Henderson) equation, the Chung-Pfost equation, the Day-Nelson (modified Henderson) equation, the Chen-Clayton equation, and the Strohman-Yoerger equation were studied by Pfost et al., (1976). Among these equations, the modified Henderson and Chung-Pfost were recognized to be more accurate than other equations over a wider range of relative humidity and various types of cereal grains (Pfost et al., 1976).

2.3. Mechanisms of Moisture Sorption Rate and Their Applications.

The following physical mechanisms have been proposed for describing the transfer of moisture in capillary porous product such as cereal grains (Brooker et al., 1974):

1. Liquid movement due to surface forces (capillary flow).
2. Liquid movement due to moisture concentration difference (liquid diffusion).
3. Liquid movement due to diffusion of moisture on the pore of surfaces (surface diffusion).
4. Vapor movement due to moisture concentration differences (vapor diffusion).
5. Vapor movement due to temperature differences (thermal diffusion).
6. Water vapor movement due to total pressure differences (hydrodynamic flow).

The well known sorption rate theories will be described and their application will be discussed in the next section.

2.3.1. Luikov's Equation (1966).

Luikov (1966) and his co-workers in the Soviet Union developed the following system of partial differential equations to describe the sorption process in porous products (Brooker et al., 1974) :

$$\partial M/\partial t = \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} P$$

$$\partial T/\partial t = \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} P$$

$$\partial P/\partial t = \nabla^2 K_{31} M + \nabla^2 K_{32} T + \nabla^2 K_{33} P$$

where M = moisture of the product

T = temperature

P = pressure

t = time.

This equation was based on non-equilibrium thermodynamic analysis. The factors K_{11}, K_{22}, and K_{33} are phenomenological coefficients, and the other K-values represent the coupling coefficient. The coupling results from the combined effects of the moisture, temperature, and total pressure gradients on moisture, energy and total mass transfer.

Even though Luikov's analysis is very thorough and fundamental in nature, it has many limitations because of the difficulty to determine all the coefficients and solve the equations involving so many partial derivatives. However, practical solutions were made by using simplifying assumptions.

One such simplified application was for desorption of moisture in cereal grains. The moisture flow due to a total pressure gradient can be neglected in the range of temperature normally employed in cereal grain drying. Consequently, the total pressure terms can be dropped and the Luikov system of equations becomes :

$$\partial M/\partial t = \nabla^2 K_{11} M + \nabla^2 K_{12} T$$

$$\partial T/\partial t = \nabla^2 K_{21} M + \nabla^2 K_{22} T.$$

The two equations above have been applied to a number of products including corn by Hussain et al. (1972). They concluded that consideration of the coupling effects of temperature and moisture in the analysis of cereal grain drying was required for a limited number of cereal grains. For yellow-dent corn the coupling effects may be neglected.

2.3.2. Pabis and Henderson's Equation (1961).

The equation developed was based on a three dimensional diffusion analysis and taking into account both a constant and a variable coefficient of internal diffusion along with appropriate set of the initial and the boundary conditions. They assumed that the grain, shelled corn, had a brick shape, 2s in thickness, 2w in width, and 2L in length. The boundary condition and the equation are as follows :

$$\frac{M(\theta,x) - M_e}{M_o - M_e} = 1 \qquad \text{when } \theta = 0$$

$$M(\theta,x) - M_e = 0 \qquad \text{at } x = -s \text{ and } x = s$$

$$\frac{\bar{M}(\theta) - Me}{Mo - Me} = \frac{512}{\pi^6} \exp\left(- \frac{\pi^2 \theta}{4} D\left(\frac{1}{s^2} + \frac{1}{w^2} + \frac{1}{L^2}\right)\right)$$

where $M(\theta)$ = the moisture at the time θ (dry basis)

M_e = the equilibrium moisture content (dry basis)

M_o = initial moisture content (dry basis)

θ = time

D = coefficient of internal diffusion.

Brooker et al. (1974) introduced the drying equation based on the mathematical diffusion by Crank (1973). They used the following initial and boundary conditions :

$$M(r,\theta) = M_o \qquad \text{when } \theta = 0$$

$$M(r_o,\theta) = M_e \quad \text{at} \quad r = r_o$$

For infinite plane :

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(- \frac{(2n+1)^2 \pi^2}{4} X^2 \right)$$

For sphere :

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(- n^2 \frac{\pi^2}{9} X^2 \right)$$

where MR = moisture ratio = $\dfrac{\bar{M}(\theta) - M_e}{M_o - M_e}$

$$X = \frac{A}{V} (D\,\theta)^{1/2}$$

A = the surface area

V = the volume of the body

θ = time

D = coefficient of internal diffusion.

For an infinete plane A/V = half thickness and for the sphere A/V = radius/3.

2.3.3. Wicke's Equation (1939).

The Wicke's equation is well known as a diffusion equation and was derived from the rate of adsorption data. Wicke assumed that the adsorbent particles were spherical, and he developed a differential equation for the diffusion of the gas toward the center of sphere. By using Pabis and Henderson's initial and boundary conditions, the final equation is as follows :

$$\frac{Q_t}{Q} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-n^2Dt)$$

where $\frac{Q_t}{Q}$ = the fraction of equilibrium amount adsorbed at at the time t

R = radius of the sphere

A = a constant

D = the diffusion coefficient

t = time.

2.3.4. Elovich and Zhabrova's Equation (1939).

Elovich and Zhabrova (1939) found that the rate of adsorption decreases exponentially with the increase of the amount of gas adsorbed.

$$dm/dt = a \exp(-\alpha m)$$

where m = amount of gas adsorbed

t = time

a, α = constants over the course of the process.

Elovich and Zhabrova studied the slow adsorption of H_2 and C_2H_4 on Ni at low temperatures. They indicated the procedure for testing equation and for determining the parameters from the experimental data. Integrating both sides, the above equation can be written in the form :

$$m = \frac{1}{\alpha} \ln (t + t_o) - \frac{1}{\alpha} \ln (t_o)$$

where $t_o = 1/\alpha a$

A plot of m vs. $\ln(t + t_o)$ should be a straight line, if t_o in this equation is chosen correctly.

Elovich and Zhabrova's equation was found to fit the experimental water adsorption data of yellow corn (Park, 1969; Park et al., 1971).

2.3.5. Patrick and Payne's Equation (1961).

This equation is based on surface adsorption models introduced by Langmuir (1918). It has been successfully applied in the study of the rate of adsorption of stearic acid on planar surfaces. The equation is as follows :

$$Qt/Q = 1 - \exp(-kt)$$

where Qt = amount of gas adsorbed at the time t

Q = amount of gas adsorbed at the end of the process

k = sorption rate constant

t = time.

2.3.6. Chung's Equation (1972).

Chung et al. (1972) introduced an adsorption model based on the assumption that sorption of water vapor on cereal grain is controlled by surface sorption mechanisms during early stages and by a diffusion mechanism in later stages. They assumed that the sorption of water vapor was a simultaneous diffusion and sorption process. With that assumption, they applied the following model to describe the adsorption process in yellow dent corn.

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right) + k(M_e - M)$$

where M = moisture content (dry basis)

M_e = equilibrium moisture content (dry basis)

r = distance from the center of the sphere

k = sorption rate constant

D = diffusion coefficient.

The initial condition and boundary conditions were :

$$M = M_o \quad \text{when } \theta = 0$$

$$M = M_e \quad \text{at } r = R,\ t > 0$$

$$\frac{\partial M}{\partial r} = 0 \quad \text{at } r = 0.$$

By applying the initial and boundary conditions and integrating over an entire sphere; the following solutions is arrived at :

$$\frac{\bar{M} - M_o}{M_e - M_o} = 1 - \frac{6}{\pi^2} \exp(-kt) \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-\bar{D}n^2 t)$$

where $\bar{M}$ = average moisture content (dry basis)

$\bar{D}$ = $D\,\pi^2/R^2$.

Among all the moisture sorption models discussed in this section, only four models were selected for fitting experimental data of this study, because these four models were simple and successfully used by many other investigators. The models were Wicke's, Elovich and Zhabrova's, Patrick and Payne's, and Chung's models.

III. MATERIAL AND METHODS

3.1. Equipment, Materials, Experimental Design, and Procedure.

3.1.1 Equipment.

An environmental chamber having inside dimensions of 9.21 m (30 ft 2 1/2 in.) length, 4.50 m (14 ft 9 in.) width, 2.59 m (8 ft 6 in.) height was used for the study (Figure 3). A refrigeration unit along with a humidifier, two electric heaters, a thermostat, and a humidistat provided the necessary facilities to keep the temperature and relative humidity constant at the desired level. The accuracy of the controlled variables were : temperature ± 1 ^{o}C and relative humidity ± 3 %. Two fans, mounted inside the chamber distributed air equally. In addition to the environmental chamber's own humidity and temperature recorders, a hygrothermograph was also used to double check the temperature and humidity recordings. Unacceptable variations in the two sets of readings could indicate equipment failure. Moistures were determined by an air-oven method and a portable battery operated electronic meter. Weighment was done by an electronic balance. Wooden dunnage 1.52 x 1.22 x 0.25 m (5 ft x 4 ft x 10 in.) were used to support the stack of bagged grain, avoid contact with the floor, and allow the aeration through the bottom part of the stack.

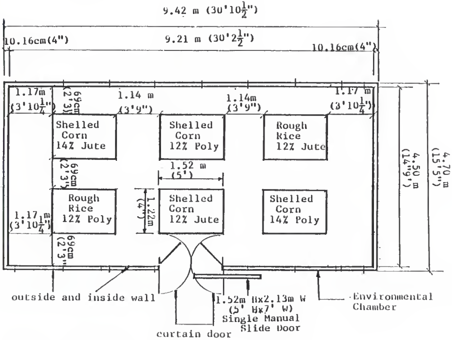


Figure 3. Location of Six Stacks of Bags in Environmental Chamber.

3.1.2. Materials.

Clean rough rice and shelled corn harvested in 1986 and 1987 were used for the experiment. Rough rice (variety New Bonet), was obtained from Winrock International plantations, Petit Jean Mountain, Arkansas and shelled corn was obtained from Farmer's Union Co-Op, Wamego, Kansas.

Two types of bags were used namely, jute and polypropylene. These bags are commonly used in warehouses in tropical countries (Isbagijo and Sumardi, 1978; Mendoza et al., 1982).

3.1.3. Experimental Design.

Shelled corn and rough rice were selected because of their importance as crops in Indonesia (Isbagijo and Sumardi, 1978) and other humid tropical countries.

Tables 1 and 2 show the variables and level of each variable studied for shelled corn and rough rice, respectively. Two levels of moisture content (12 % and 14 % wet basis) for shelled corn and one level (12 % wet basis) for rough rice were tested. For each type of grain, three levels of relative humidity (70 %, 80 %, and 90 %) were studied. Two types of bag materials (jute and polypropylene) were included. Temperature was kept constant at 26.7 ^{o}C (80 ^{o}F) for all experiments.

Table 1. Experimental Design for Shelled Corn.

Initial moisture	2 levels	12 %	14 %	
Relative humidity	3 levels	70 %	80 %	90 %
Bag material	2 levels	Jute and Polypropylene		
Temperature	1 level	26.7 °C (80 °F)		

Table 2. Experimental Design for Rough Rice.

Initial moisture	1 level	12 %		
Relative humidity	3 levels	70 %	80 %	90 %
Bag material	2 levels	Jute and Polypropylene		
Temperature	1 level	26.7 °C (80 °F)		

Under normal conditions, effect of relative humidity on grain deterioration is more important than temperature because increased relative humidity indicates increased availability of water to insects and microorganisms. This enhances the biological activity in the product (Pixton and Warburton, 1971). Also, to reduce the size and time of the experiment, only one level of temperature was used.

Average monthly relative humidities in Jakarta, Indonesia range from 68 to 89 % and average monthly temperatures range from 25.3 to 28.2 °C (Center of Meteorology and Geophysics, 1985). To simulate the conditions in

Jakarta, 70 %, 80 %, and 90 % relative humidities and 26.7 ^{o}C (80 ^{o}F) temperature were chosen.

The experimental design shown in Table 1 and 2 results in 18 treatment combinations for both grains. To obtain meaningful and useful information about the sorption process in bagged grain, a few months (at least 3 months) of observation for each treatment combination would be neccesary. For 18 treatment combinations without even any replicate, this would require a long experimentation time making the research unwieldy. It was, therefore, decided to use six stacks of grain (6 treatment combinations) simultaneously and subject them to the same temperature, relative humidity, and time combinations. This approach reduced the required time drastically, thus making it possible to complete the experiment in about a year.

3.1.4. Procedure.

Experiments were conducted at Food and Feed Grain Institute (FFGI) laboratory, at Kansas State University. The experiment basically consisted of measurement of moisture change of shelled corn and rough rice in jute and polypropylene bags as a function of time under a constant temperature and relative humidity environment.

As-purchased average moisture content of one lot of shelled corn was 12 %, the second lot was 14 % and one lot of rough rice was 12 %. However, there was a variation of moisture among bags. The grain which had more moisture than the desired level was first dried by spreading the grain in the environmental chamber under controlled temperature and relative humidity setting. The moisture was monitored very frequently and the drying was stopped as soon as the desired moisture was obtained. The grain which was found to have less moisture than the desired level was also spread in the environmental chamber to adsorb moisture.

The grain was bagged into two types of bags, jute and polypropylene. Each bag contained 45.4 kg (100 lbs) of shelled corn and 34.0 kg (75 lbs) of rough rice. The bagged grains were stacked on wooden dunnage. Each stack had an approximate dimensions of 0.91 x 0.91 x 0.91 m (3 x 3 x 3 ft). There were 14 bags on each stack and the bags were piled up to seven layers (Figure 4).

Before stacking in the environmental chamber, all bagged grains were fumigated, eventhough there was no visible signs of insect infestations in grains. Recommended dosage and exposure time for bagged grain is 1 tablet of aluminum Phospide per m^3 (30 tablets per 1000 ft^3) of stack size and 3 days respectively (Degesch America, 1987). At this rate seven tablets were used to fumigate for 3 days of 6.8 m^3 (240 ft^3) of stack volume needed for each set of experiment. Twenty one tablets were used for all experiments. The bagged grains were then stored in the environmental chamber for 3 months.

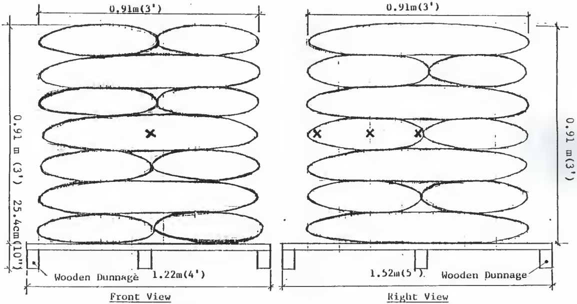


Figure 4. Arrangement of Bags and Grain Sampling Points in Stack.

The stack of bagged grain was designed as a cube (0.91 x 0.91 x 0.91 m), for the sake of symmetry about the center which makes engineering analysis relatively less complex. Consequently the grain moisture variation became symmetric about the center. This transformed the study into a one-dimensional problem. Therefore, samples were taken along one direction only from three different places in the stacks namely, 0 cm (0 in.) (stack surface), 46 cm (1.5 ft) from the surface (center), and 22.86 cm (9 in.) from the surface (in between) (Figure 4). Grain moisture was monitored every 3 days by obtaining about 30 grams of shelled corn samples and about 20 grams of rough rice samples from each location. This time interval was determined by a preliminary study which indicated that more frequent readings were unnecessary.

Samples were taken by a specially designed sampling probe (Figure 5). This device consisted of two concentric tubes with an inner tube having an outside diameter of 1.69 cm (2/3 in.), an outer tube of size 1.91 cm (3/4 in.) outside diameter, and only one sampling hole of 3.87 cm^2 (0.6 in^2.) area. The moisture content of rough rice was determined by an oven drying method adapted from Hart et al. (1959), as cited by Sukabdi (1979). The 20 gm sample was equally divided to obtain two moisture readings for each location. Each 10 gm rough rice was dried in air-oven at 130 ^oC for 22 hours and then reweighed after being cooled in a dessicator to room temperature. The moisture content was calculated from the difference between initial and final weights and expressed in percentage, wet basis. The same procedure was used to determine the moisture content of shelled corn. The oven setting for shelled corn was at 103 °C for 72 hours (Stroshine et al., 1984).

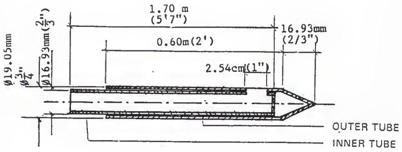


Figure 5. Grain Sampling Probe.

IV. RESULTS AND DISCUSSION

4.1 Effects of Locations in Stack and Relative Humidity on Moisture Sorption.

Moisture sorption data are presented in 18 tables. Out of these tables only 3 are given in this section as samples and the remaining data have been presented in Appendix A.

Experimental data is presented in Tables 3, 4, 5, and Appendix A. Only shelled corn at 14 % initial moisture content, 70 % relative humidity, and 26.7°C (Table A-4) was in a desorption process while other treatment combinations resulted in adsorption.

Tables 3, 4, Figures 6, and 7 show the moisture sorption rate of shelled corn in jute bags at various positions in the stack for 12 %, and 14 % initial moisture, 90 % relative humidity, and 26.7 °C. The moisture varied with positions in the stack of bagged grain. The grain at the surface adsorbed more moisture than the center of the stack, or the point in between because of the greater surface area exposed to the environment.

The moisture increased rapidly up to about 30 days, especially, when the grain at 12 % initial moisture was exposed to 90 % relative humidity. According to Pixton and Warburton (1971), when grain is exposed to a wet atmosphere, 90 % of moisture change occurs with 5 to 14

Table 3. Moisture Sorption of Shelled Corn at 12 % Initial Moisture in Stack of Jute Bags Stored under 90 % Relative Humidity and 26.7 ^{o}C (80 ^{o}F).

Days	Moisture content (% wet basis)[a]			
	Surface	In between	Center	Average
0	12.01	11.98	12.03	12.01
3	12.10	12.07	12.03	12.07
6	12.42	12.27	12.17	12.29
9	12.57	12.48	12.42	12.49
12	12.68	12.59	12.41	12.58
15	12.88	12.57	12.57	12.87
18	12.90	12.83	12.66	12.80
21	13.10	12.89	12.83	12.87
24	13.25	12.82	12.78	12.95
27	13.24	12.94	12.88	13.02
30	13.33	12.94	12.88	13.05
33	13.47	13.00	13.00	13.18
38	13.53	13.17	13.10	13.27
39	13.50	13.20	13.21	13.30
42	13.56	13.21	13.19	13.32
45	13.66	13.20	13.21	13.36
48	13.65	13.33	13.25	13.41
51	13.75	13.30	13.33	13.46
54	13.74	13.30	13.34	13.48
57	13.84	13.38	13.37	13.52
60	13.88	13.36	13.38	13.54
63	13.96	13.40	13.37	13.58
66	14.00	13.44	13.47	13.84
69	13.99	13.51	13.50	13.87
72	14.05	13.66	13.53	13.75
75	14.05	13.88	13.52	13.75
78	14.15	13.68	13.52	13.78
81	14.18	13.68	13.87	13.83
84	14.20	13.65	13.69	13.85
87	14.19	13.70	13.70	13.86
90	14.22	13.81	13.79	13.94

[a] Average of 2 moisture readings.

Table 4. Moisture Sorption of Shelled Corn at 14 % Initial Moisture in Stack of Jute Bags Stored under 90 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% wet basis)[a]			
	Surface	In between	Center	Average
0	14.04	14.00	14.03	14.02
3	14.06	14.00	14.02	14.03
6	14.25	14.18	14.12	14.18
9	14.31	14.19	14.18	14.23
12	14.40	14.18	14.17	14.25
15	14.49	14.30	14.27	14.35
18	14.62	14.33	14.34	14.43
21	14.78	14.40	14.33	14.50
24	14.86	14.41	14.43	14.57
27	15.11	14.42	14.43	14.65
30	15.16	14.40	14.43	14.66
33	15.28	14.43	14.49	14.73
36	15.27	14.49	14.48	14.75
39	15.34	14.50	14.47	14.77
42	15.36	14.51	14.47	14.78
45	15.36	14.51	14.47	14.78
48	15.37	14.60	14.49	14.82
51	15.38	14.66	14.55	14.86
54	15.36	14.80	14.57	14.84
57	15.42	14.63	14.58	14.88
60	15.43	14.64	14.58	14.88
63	15.46	14.65	14.59	14.90
66	15.46	14.64	14.62	14.91
69	15.48	14.66	14.63	14.92
72	15.50	14.70	14.65	14.95
75	15.49	14.72	14.65	14.95
78	15.52	14.73	14.70	14.98
81	15.55	14.72	14.68	14.98
84	15.60	14.72	14.68	15.00
87	15.63	14.73	14.68	15.01
90	15.79	14.74	14.70	15.08

[a] Average of 2 moisture readings.

Table 5. Moisture Sorption of Rough Rice at 12 % Initial Moisture in Stack of Jute Bags Stored under 90 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% wet basis)[a]			
	Surface	In between	Center	Average
0	12.00	12.02	11.98	12.00
3	12.06	12.08	12.03	12.06
6	12.19	12.10	12.11	12.13
9	12.36	12.21	12.19	12.25
12	12.44	12.33	12.20	12.32
15	12.47	12.32	12.25	12.35
18	12.47	12.31	12.29	12.36
21	12.50	12.33	12.34	12.39
24	12.61	12.36	12.32	12.43
27	12.66	12.40	12.31	12.46
30	12.78	12.41	12.35	12.51
33	12.88	12.53	12.40	12.60
36	12.90	12.55	12.39	12.61
39	12.95	12.53	12.44	12.64
42	13.00	12.55	12.48	12.68
45	13.00	12.56	12.50	12.69
48	13.05	12.87	12.58	12.77
51	13.10	12.66	12.60	12.79
54	13.09	12.70	12.59	12.79
57	13.10	12.71	12.65	12.82
60	13.15	12.77	12.64	12.85
63	13.13	12.80	12.68	12.86
66	13.16	12.81	12.78	12.92
69	13.18	12.90	12.82	12.97
72	13.19	12.91	12.85	12.98
75	13.18	12.90	12.82	12.97
78	13.20	12.91	12.85	12.99
81	13.25	12.92	12.84	13.00
84	13.26	12.93	12.85	13.01
87	13.30	12.91	12.87	13.03
90	13.30	12.93	12.90	13.04

[a] Average of 2 moisture readings.

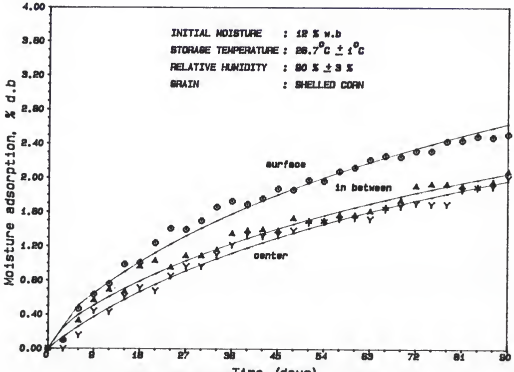


Figure 6. Moisture Sorption Rate of Grain in Stack of Jute Bags.

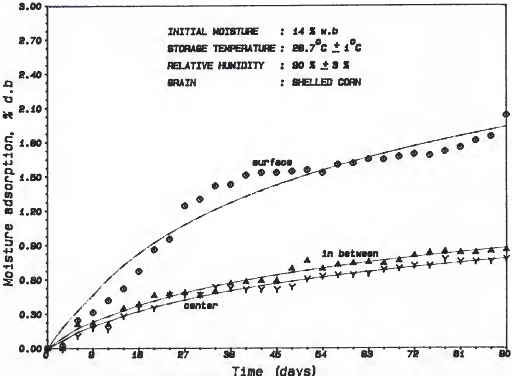


Figure 7. Moisture Sorption Rate of Grain in Stack of Jute Bags.

days, depending on the type, condition, and quantity of the grain.

There was a small change in the moisture sorption at various stack positions with respect to time. However, at the surface of the stack of jute bags, stored under 90 % relative humidity for 30 days, the shelled corn at 14 % initial moisture increased to about 16 % level (Table 4). At this moisture level, the grains become very prone to insect and fungal deterioration. A similar result was also observed for shelled corn in polypropylene bags stored for more than 51 days at the same initial moisture and environmental conditions.

Table 5 and Figure 8 show the moisture sorption rate of rough rice at 12 % initial moisture, subjected to 90 % relative humidity and 26.7 ^{o}C. Like shelled corn, moisture increased rapidly up to about 30 days. The rapid moisture increase was also observed for rough rice subjected to other sets of environmental conditions. The rough rice in jute bags at 90 % relative humidity did not reach as high a moisture level as shelled corn. After 90 days, the surface moisture increased to only 13.30 %. However, in general, variations in the moisture adsorption rate at three locations were similar to shelled corn. The other sets of treatment combinations for rough rice are shown in Appendix A. They also show the same type of variations of moisture adsorption rate.

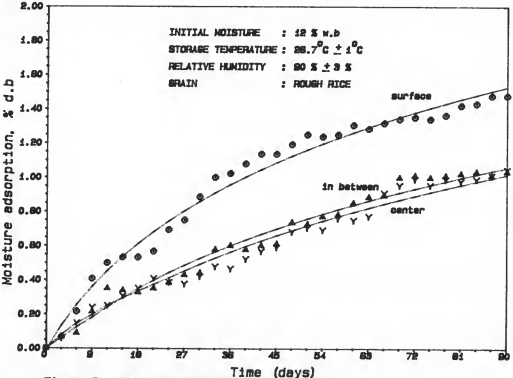


Figure 8. Moisture Sorption Rate of Grain in Stack of Jute Bags.

Table 6 shows the differences of grain moisture at the surface and in the center. The differences increased with the relative humidity for the same initial moisture and type of the bag. At higher relative humidities, a greater water vapor pressure difference between the grain and environmental air exists. Since the grain at the surface was exposed to environmental air, at a higher relative humidity the grain adsorbed more moisture. However, at the center the grain moisture increased relatively slowly because a considerable barrier was created by the grain around the center and the material of the bag. In addition, there was no forced convection of air. Shelled corn in jute bags at 14 % initial moisture 90 % relative humidity had the most moisture difference.

The difference between average initial and final moisture is shown in Table 7. The shelled corn in jute bags stored for 90 days at initial moisture of 12 %, 90 % relative humidity, and 26.7 ^{o}C adsorbed the most moisture because of the highest water vapor pressure difference between the grain and air.

For all the experiments the grain did not have enough time to reach the equilibrium moisture content with corresponding environmental air (Table 8). If the grain is exposed in a thin layer of a few kernel thickness, the time required to reach equilibrium may be as low as a week

Table 8. Differences of Moisture between Various Positions in Stack of Bags at 26.7 °C (80 °F) after 30, 60, and 90 Days.

Grain	Initial Moisture (% w.b.)	Environmental Conditions (% r.h.)	Moisture Differences (% Wet Basis) Surface - Center 30 days	60 days	90 days
Shelled Corn	12	70			
jute			0.05	0.08	0.14
poly			0.04	0.07	0.08
	12	80			
jute			0.38	0.45	0.53
poly			0.06	0.16	0.24
	12	90			
jute			0.45	0.50	0.58
poly			0.25	0.25	0.32
	14	80			
jute			0.73	0.72	0.74
poly			0.35	0.48	0.49
	14	90			
jute			0.73	0.85	1.09
poly			0.35	0.55	0.83
Rough Rice	12	70			
jute			0.25	0.31	0.38
poly			0.19	0.27	0.30
	12	80			
jute			0.38	0.46	0.54
poly			0.22	0.34	0.40
	12	90			
jute			0.43	0.53	0.60
poly			0.17	0.41	0.51

Table 7. Difference between Average Initial and Final Moisture Content in % Wet Basis at 26.7 °C (80 °F).[a]

Grain	Environmental Conditions	Bag	Initial	Final (90 days)	Difference
Shelled Corn	70 % r.h.	jute	11.99	13.40	1.41
		poly	11.89	12.45	0.56
	80 % r.h.	jute	12.03	13.83	1.60
		poly	12.01	13.35	1.34
	90 % r.h.	jute	12.01	13.94	1.93
		poly	12.00	13.52	1.52
	80 % r.h.	jute	13.99	14.95	0.96
		poly	13.98	14.77	0.79
	90 % r.h.	jute	14.02	15.08	1.08
		poly	14.02	14.94	0.92
Rough rice	70 % r.h.	jute	11.88	12.54	0.66
		poly	11.96	12.45	0.49
	80 % r.h.	jute	12.00	12.73	0.73
		poly	12.00	12.53	0.53
	90 % r.h.	jute	12.00	13.04	1.04
		poly	11.99	12.94	0.95

a

Average of moisture at surface, in between, and center.

Table 8. Relationships between Average Initial and Final Moisture in % Wet Basis and Equilibrium Moisture Content (E.M.C) at Various Relative Humidities and 28.7 °C (80 °F).[a]

Grain	Environmental Conditions	Bag	Initial	Final (90days)	E.M.C[b]
Shelled Corn	70 % r.h.	jute	11.99	13.40	13.88
		poly	11.89	12.45	
	80 % r.h.	jute	12.03	13.63	15.89
		poly	12.01	13.35	
	90 % r.h.	jute	12.01	13.94	18.91
		poly	12.00	13.52	
	70 % r.h.	jute	14.01	13.75	13.88
		poly	14.01	13.76	
	80 % r.h.	jute	13.99	14.95	15.89
		poly	13.98	14.77	
	90 % r.h.	jute	14.02	15.08	18.91
		poly	14.02	14.94	
Rough rice	70 % r.h.	jute	11.88	12.54	13.13
		poly	11.89	12.45	
	80 % r.h.	jute	12.00	12.73	14.72
		poly	12.00	12.53	
	90 % r.h.	jute	12.00	13.04	16.98
		poly	11.99	12.94	

[a] Average of moisture at surface, in between, and center.

[b] The E.M.C was calculated using Chung and Pfost's equation.

but an increase in the thickness of the the layer greatly extends the period required to reach equilibrium (Pixton and Griffiths, 1971).

For the same environmental conditions, initial moisture content, and time the final moisture of rough rice was less than the final moisture of shelled corn because the equlibrium moisture content for rough rice was less than shelled corn.

4.2. Effects of Initial Moisture Content on Moisture Sorption.

Tables 9, 10, and 11 show the effect of initial moisture content on moisture sorption rate of shelled corn and rough rice at various relative humidities of the environmental air. At the same temperature and relative humidity, the amount of moisture adsorbed by grain increased at lower initial moisture content. Such an effect can be explained by the fact at a lower initial moisture content of grain, there exists a greater water vapor pressure difference between the grain and environmental air (Brooker et al., 1974; Henderson and Perry, 1976).

Tables 9 and 10 show that at the 90 % relative humidity the difference in percent moisture adsorbed by shelled corn at 12 % (w.b) and 14 % (w.b) initial moisture was the

Table 9. Cumulative Percent Moisture Adsorbed by Shelled Corn (% Dry Basis) at 12 % Initial Moisture Content, 26.7 ^{o}C (80 ^{o}F) and Various Relative Humidities.

Days	Jute			Polypropylene		
	Relative Humidity					
	70%	80%	90%	70%	80%	90%
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0190	0.0304	0.0882	0.0076	0.0038	0.0380
6	0.1023	0.1213	0.3182	0.0303	0.0798	0.1175
9	0.1818	0.3373	0.5492	0.2198	0.1591	0.1743
12	0.3258	0.4131	0.8288	0.2692	0.3031	0.3409
15	0.3902	0.3373	0.7576	0.4281	0.3878	0.5682
18	0.4356	0.5723	0.8978	0.3678	0.3713	0.6289
21	0.5078	0.6821	0.9848	0.3678	0.3789	0.6478
24	0.5341	0.7162	1.0720	0.3144	0.4092	0.7500
27	0.5603	0.7958	1.1518	0.4585	0.5039	0.8409
30	0.5947	0.8185	1.1857	0.5039	0.5380	0.8978
33	0.9166	0.8185	1.3089	0.5759	0.7312	0.9859
36	0.9772	0.9435	1.4319	0.5835	0.8714	1.0494
39	0.9848	0.9890	1.4735	0.8020	0.8638	1.1062
42	1.0075	1.0725	1.4925	0.6782	0.9509	1.2046
45	1.0908	1.1595	1.5342	0.8972	0.8547	1.2312
48	1.1439	1.2240	1.5948	0.7009	0.9964	1.3182
51	1.2197	1.2505	1.6516	0.7047	1.0570	1.3410
54	1.2538	1.3567	1.6516	0.7350	1.0911	1.3713
57	1.2575	1.3794	1.7235	0.7464	1.1859	1.3940
60	1.2765	1.4021	1.7425	0.7691	1.2047	1.4357
63	1.2726	1.4778	1.7842	0.7426	1.2123	1.4546
66	1.3030	1.4817	1.8524	0.7501	1.2237	1.4887
69	1.3219	1.5574	1.8865	0.8222	1.2351	1.5190
72	1.3447	1.5574	1.9774	0.8373	1.2388	1.5342
75	1.3825	1.6370	1.9812	0.8524	1.2692	1.5986
78	1.4734	1.7128	2.0190	0.8638	1.3184	1.6213
81	1.4734	1.7543	2.0721	0.8790	1.3752	1.6630
84	1.5757	1.7810	2.0911	0.8904	1.4320	1.6554
87	1.5757	1.8075	2.1099	0.9245	1.4889	1.8971
90	1.5984	1.8114	2.1971	0.9206	1.5192	1.7273

Table 10. Cumulative Percent Moisture Adsorbed by Shelled Corn (% Dry Basis) at 14 % Initial Moisture Content, 26.7 °C (80 °F) and Various Relative Humidities.

Days	Jute			Polypropylene		
	Relative Humidity					
	70% *)	80%	90%	70% *)	80%	90%
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0052	0.0155	0.0040	0.0485	0.0241	0.0156
6	0.0311	0.0852	0.1861	0.0820	0.0706	0.0504
9	0.0750	0.2364	0.2366	0.1280	0.0782	0.0891
12	0.1267	0.2712	0.2637	0.1183	0.1247	0.1434
15	0.1797	0.3061	0.3838	0.1667	0.1906	0.1821
18	0.2249	0.3566	0.4730	0.1707	0.2294	0.2210
21	0.3218	0.4573	0.5583	0.2327	0.2914	0.2791
24	0.3980	0.5077	0.8320	0.3219	0.3534	0.3373
27	0.3774	0.6473	0.7328	0.3257	0.4231	0.3760
30	0.3994	0.7131	0.7444	0.3877	0.5123	0.4768
33	0.4083	0.7131	0.8181	0.4110	0.5278	0.5815
36	0.4356	0.7363	0.8414	0.4537	0.5859	0.6086
39	0.4265	0.7635	0.8685	0.3761	0.6063	0.6706
42	0.4213	0.7944	0.8801	0.4150	0.6478	0.8969
45	0.4278	0.8100	0.8801	0.4072	0.8750	0.7327
48	0.3787	0.8255	0.9268	0.3528	0.6789	0.7482
51	0.3851	0.8487	0.9770	0.3567	0.7021	0.7831
54	0.3812	0.8487	0.9537	0.3452	0.7332	0.8102
57	0.3747	0.8565	0.9926	0.3568	0.7448	0.8218
60	0.3747	0.8952	1.0003	0.3606	0.7525	0.8806
63	0.3645	0.9185	1.0197	0.3606	0.7951	0.8683
66	0.3838	0.9766	1.0275	0.3568	0.8184	0.8839
69	0.3554	0.9728	1.0468	0.3373	0.8262	0.8955
72	0.3529	0.9921	1.0779	0.3452	0.8494	0.9228
75	0.3618	1.0193	1.0817	0.3335	0.8300	0.9808
78	0.3502	1.0348	1.1166	0.3219	0.8494	0.9886
81	0.3580	1.0386	1.1166	0.3179	0.8727	0.9962
84	0.3515	1.0502	1.1360	0.3296	0.8959	1.0273
87	0.3502	1.0851	1.1515	0.3257	0.8959	1.0487
90	0.3489	1.1123	1.2252	0.3219	0.9192	1.0738

*) Desorbed moisture

Table 11. Cumulative Percent Moisture Adsorbed by Rough Rice (% Dry Basis) at 12 % Initial Moisture Content, 26.7 ^{o}C (80 ^{o}F) and Various Relative Humidities.

Days	Jute			Polypropylene		
	Relative Humidity					
	70%	80%	90%	70%	80%	90%
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0908	0.0588	0.0644	0.0642	0.0568	0.0416
6	0.1475	0.1250	0.1515	0.0869	0.1250	0.1174
9	0.1968	0.1932	0.2878	0.1362	0.1818	0.1855
12	0.1929	0.2273	0.3674	0.1664	0.1894	0.2915
15	0.2459	0.2388	0.3940	0.2004	0.2083	0.3105
18	0.2913	0.2500	0.4053	0.2534	0.2159	0.3408
21	0.2951	0.2814	0.4432	0.2458	0.2349	0.3873
24	0.3405	0.4318	0.4886	0.2572	0.2803	0.3863
27	0.3821	0.4432	0.5190	0.2912	0.3295	0.4279
30	0.3784	0.5000	0.5832	0.3253	0.3940	0.4431
33	0.4011	0.5227	0.6858	0.3442	0.4394	0.4886
36	0.4085	0.5568	0.6969	0.3442	0.4735	0.5301
39	0.4199	0.5682	0.7272	0.3593	0.4924	0.5795
42	0.4539	0.6932	0.7690	0.3783	0.5190	0.6400
45	0.4842	0.6705	0.7803	0.4313	0.5492	0.6704
48	0.4880	0.6818	0.8713	0.4464	0.5795	0.7044
51	0.5107	0.6818	0.8940	0.4804	0.6023	0.7536
54	0.5410	0.7159	0.9015	0.4880	0.6288	0.7650
57	0.5713	0.7386	0.9318	0.5031	0.6250	0.8218
60	0.5826	0.7386	0.9897	0.5145	0.6364	0.8258
63	0.5837	0.7386	0.9810	0.5182	0.6401	0.8835
66	0.5940	0.7500	1.0417	0.5334	0.6514	0.8749
69	0.5884	0.7500	1.0985	0.5334	0.6591	0.8978
72	0.5940	0.7500	1.1174	0.5372	0.6818	0.9241
75	0.6242	0.7841	1.0985	0.5144	0.6969	0.9695
78	0.6848	0.7841	1.1213	0.5749	0.6894	0.9960
81	0.6999	0.7955	1.1401	0.6090	0.6969	1.0226
84	0.7302	0.8068	1.1515	0.6090	0.6969	1.0263
87	0.7377	0.8068	1.1687	0.6168	0.7083	1.0453
90	0.7415	0.8068	1.1856	0.6430	0.7273	1.0869

After 90 days, the difference was 0.97 % for jute bag and 0.65 % dry basis for polypropylene bag. The difference between percent moisture adsorbed by shelled corn at initial moisture 14 % w.b and rough rice at initial moisture 12 % w.b stored under 90 % relative humidity was very small. After 30, 60, and 90 days, in jute bags the difference was 0.16, 0.03, and 0.04 percent dry basis, respectively and in polypropylene bags was 0.03, 0.04, and 0.01 percent dry basis, respectively (Tables 10, 11, and Figure 9).

4.3. Effects of Type of Bag on Moisture Sorption.

The effect of bag materials on moisture sorption rate is shown in Figure 10. Jute bags were more porous than polypropylene bags, allowing more air movement. Tables 9, 10, and 11 and Figure 10 show that the grain contained in jute bags adsorbed more moisture as a percent of total moisture than in polypropylene bags. However, shelled corn at 14 % initial moisture stored in jute bags under 70% relative humidity and 26.7 ^{o}C desorbed more moisture than polypropylene bags. Jute bags being more porous than polypropylene bags allowed air movement in and out of the bags more readily.

Table 12 shows that at the same relative humidity, the difference between final moisture of shelled corn in jute and polypropylene bags increased when the initial moisture

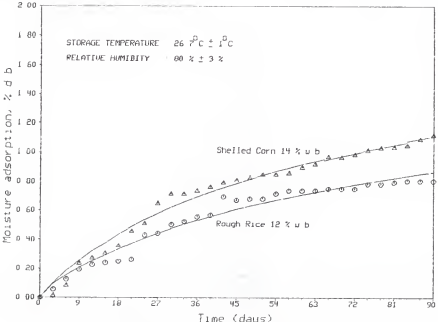


Figure 9 Effect of Initial Moisture on Moisture Sorption Rate of Grain in Stack of Jute Bags

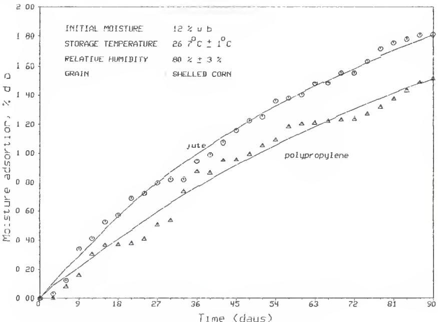


Figure 10 Effect of Bag Materials on Moisture Sorption Rate of Grain

decreased. At the same initial moisture and relative humidity, shelled corn had a larger difference than rough rice.

Table 12. Difference between Average Final Moisture Content (% Wet Basis) of Grain in Jute and Polypropylene Bags at 26.7 °C (80 °F).[a]

Grain	Relative Humidity (%)	Initial Moisture (% W.B)	Final Moisture		Difference
			Jute	Poly	
Corn	70	12	13.40	12.45	0.95
	80	12	13.83	13.35	0.28
	90	12	13.94	13.52	0.42
	70	14	13.75	13.78	0.01
	80	14	14.95	14.77	0.18
	90	14	15.08	14.94	0.14
Rice	70	12	12.54	12.45	0.09
	80	12	12.73	12.53	0.20
	90	12	13.04	12.94	0.10

[a] Average of moisture at surface, in between, and center.

4.4. Application of Adsorption Rate Models.

To explain the sorption phenomena, it is helpful to characterize the process by mathematical models so as to study the effects of the principal parameters involved.

The equation should fit into the experimental data well. Various equations were discussed in Chapter II. For reasons explained earlier, Chung's, Patrick and Payne's, Wicke's, and Elovich and Zhabrova's equations, were fitted into the experimental data. Figure 11 shows that the Chung's adsorption equation fitted into the data well, but Patrick and Payne's, and Wicke's equations did not fit well into the experimental data. Models sometime do not fit the experimental data because of the inappropriate boundary conditions and the oversimplification of the equations (Brooker et al., 1974).

The Chung adsorption rate equation presented the adsorbed-phase diffusion combined with internal surface adsorption which was the rate-controlling mechanism of water vapor adsorption by grain. The moisture adsorption rate of the grain was controlled by internal diffusion mechanism and another mechanism such as surface adsorption which may play a significant role especially during the initial stage of the sorption kinetic process. Therefore, Chung's adsorption rate equation was capable to describe the process entirely. Table 13 shows the values of the parameters in the Chung adsorption rate equation obtained from experimental data. The two parameters, k and D, was obtained using Linearization Technique (Draper and Smith, 1981). The algorithm can be written as follows:

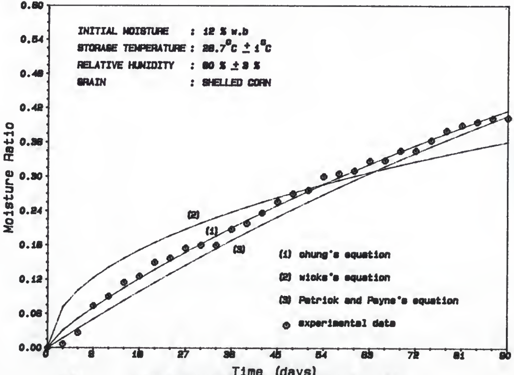


FIGURE 11. TEST OF MOISTURE SORPTION RATE EQUATIONS OF GRAIN IN STACK OF JUTE BAGS.

Table 13. Values of Parameters in Chung's Adsorption Rate Equation.

Environmental Conditions	Grain	Bag	Initial Moisture (w.b)	k (days^{-1})	$\bar{D}$ (days^{-1})
Temp. = 26.7°C, R.H = 70 %	Corn	Jute	12%	0.01201	0.00076
		Poly		0.00356	0.00061
	Rice	Jute	12%	0.00439	0.00403
		Poly		0.00078	0.00045
Temp. = 26.7°C, R.H = 80%	Corn	Jute	12%	0.00493	0.00008
		Poly		0.00427	0.00001
		Jute	14%	0.00480	0.00070
		Poly		0.00490	0.00015
	Rice	Jute	12%	0.00131	0.00057
		Poly		0.00150	0.00019
Temp. = 26.7°C, R.H = 90%	Corn	Jute	12%	0.00115	0.00037
		Poly		0.00151	0.00011
		Jute	14%	0.00046	0.00033
		Poly		0.00199	0.00001
	Rice	Jute	12%	0.00124	0.00012
		Poly		0.00151	0.00003

$$f(e,\theta) = f(e,\theta_o) + \sum_{i=1}^{p} [\frac{f(e,\theta)}{\theta_i}]_{\theta=\theta_o} (\theta_i - \theta_{io})$$

where $f(e,\theta)$ = taylor series expansion of the model, $f(e,\theta)$

θ_i = parameter of the model, i = 1,2,3, ...p

θ_{io} = initial value of parameter, i = 1,2,3,.p.

If we set,

$$f_u^o = f(e,\theta)$$

$$B_i^o = \theta_i - \theta_{io}$$

$$Z_{iu}^o = [\frac{\partial f(e,\theta)}{\partial \theta_i}]_{\theta=\theta_o}$$

we can estimate the parameters B_i^o, i =1,2,3 ... p by using the equation as follows :

$$b_o = (Z_o' Z_o)^{-1} Z_o' (Y - f^o)$$

where b_o = vector containing the estimated parameters of of the model

Z_o = matrix containing the derivation of the model with respect to the parameter

Z_o' = transpose of matrix Z_o

$Y - f^o$ = vector containing the differences between the magnitude of the model using revised and previous parameters.

The error of sum of the squares, $S(\Theta)$, is a function of Θ, parameters, and can be written as follows :

$$S(\Theta) = \sum_{u=1}^{n} \{ Yu - f(e,\Theta)\}^2.$$

The revised parameters were then used to estimate the model. If the difference of $S(\Theta)$ using the revised and previous parameters was still large, the iteration was continued. Iterations were stopped until the difference of the $S(\Theta)$ was less than 10^{-8}.

The error of sum of the squares may oscillate widely as increasing or decreasing. To avoid these deficiences, the vector b_j containing estimated parameters at j^{th} iteration was corrected by halving it if

$$S(\Theta_{j+1}) > S(\Theta_j)$$

or doubling it if

$$S(\Theta_{j+1}) < S(\Theta_j).$$

This halving or doubling process was continued till the end of iteration.

The above algorithm was used to write the FORTRAN program presented in Appendix D.

The diffusion coefficient of a single kernel wheat was independent of moisture content in the commercially important drying range of 12 - 30 % (dry basis) (Becker and

Salans, 1956). Diffusion at lower than 65 °C were practically independent of variety (Fan et al., 1961). The diffusion coeficient was found to depend on the type of bag. Grain in jute bags had a value of diffussion coefficient greater than grain in polypropylene bags. This is one of the reasons why grain in jute bags adsorbed and desorbed moisture more readily than polypropylene bags. The values of the parameter (k, and D) of shelled corn were greater than those of rough rice.

The values of parameters in Table 13 were not only very small, they also did not change much as such the moisture sorption of grain in the stack of jute and polypropylene bags was a slow process. The slow process was also due to the resistance of the bags and multi-molecular layers of water at the initial stage of the moisture sorption. The slow diffusion of water was followed after the completion of initial stage. In general, the rate of moisture exchange with the environmental air is slower than is usually expected, especially when the grain is stored in a large quantity (Pixton and Griffiths, 1971).

Figures 12 , through 19 and Tables presented in Appendix B show the comparison between calculated values by using the Chung's equation and experimental data. Square of the coefficient of correlation (R^2) for each treatment combination was higher than 0.97 (Table 14) which meant that the Chung adsorption equation fitted the data well.

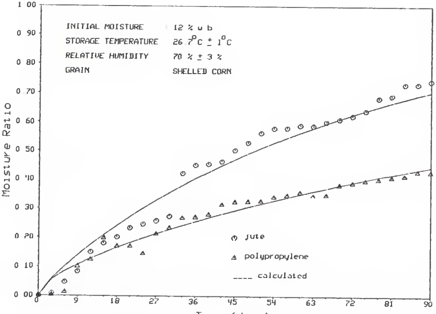


FIGURE 12 COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING CHUNG'S EQUATION

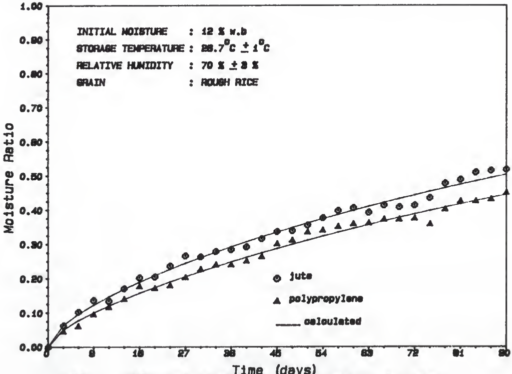


FIGURE 13. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING CHUNG'S EQUATION.

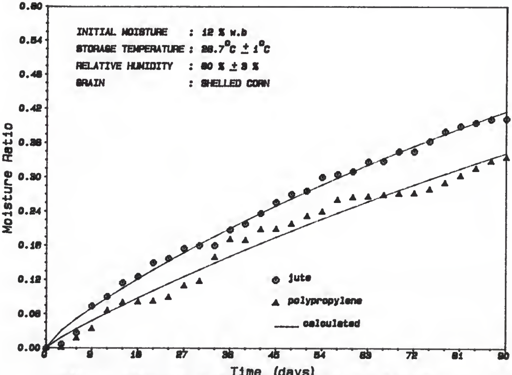


FIGURE 14. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING CHUNG'S EQUATIONS.

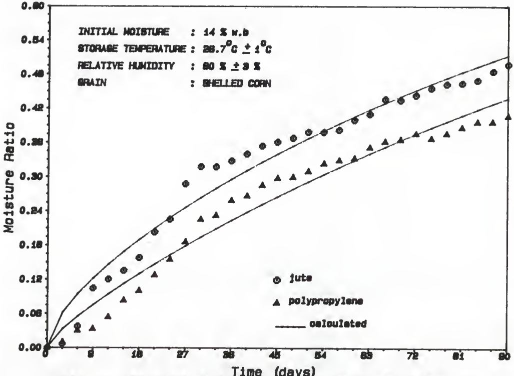


FIGURE 15. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING CHUNG'S EQUATIONS.

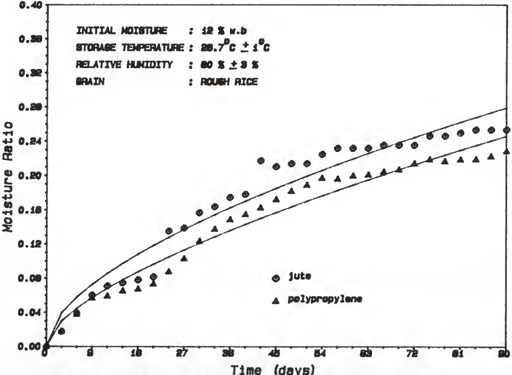


FIGURE 16. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING CHUNG'S EQUATION.

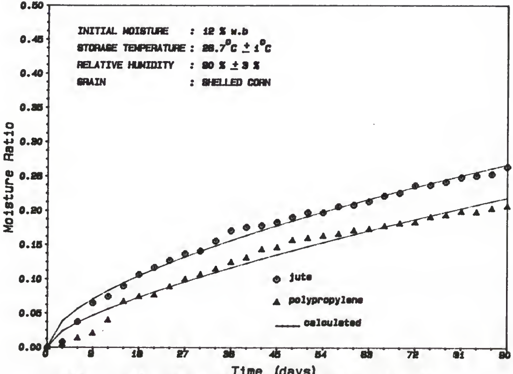


FIGURE 17. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN USING CHUNG'S EQUATION.

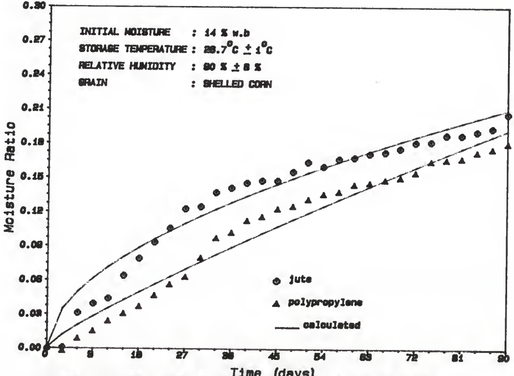


FIGURE 18. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN USING CHUNG'S EQUATION.

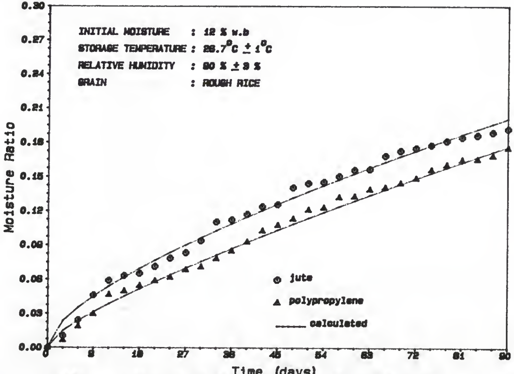


FIGURE 19. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING CHUNG'S EQUATION.

Table 14. Square of Correlation Coefficient (R^2) for Chung's Adsorption Rate Equation.

Treatment Combinations				R^2
Grain	Bag	Moisture (% w.b)	R.H (%)	
Corn	jute	12	70	0.9913
	poly	12	70	0.9817
	jute	12	80	0.9972
	poly	12	80	0.9891
	jute	14	80	0.9845
	poly	14	80	0.9835
	jute	12	90	0.9938
	poly	12	90	0.9871
	jute	14	90	0.9808
	poly	14	90	0.9847
Rice	jute	12	70	0.9951
	poly	12	70	0.9950
	jute	12	80	0.9749
	poly	12	80	0.9832
	jute	12	90	0.9953
	poly	12	90	0.9971

The Elovich and Zhabrova's equation which describes the relationship between time and the amount of gas adsorbed also fitted the experimental data well. The R^2 values and the parameters of the equation are presented in Table 15 and 16 respectively. Figures 20 through 27 and Tables presented in Appendix C show the comparison between experimental data and calculated values by using Elovich and Zhabrova's equation.

Table 15. Square of Correlation Coefficient (R^2) for Elovich and Zhabrova's Equation.

Treatment Combinations				R^2
Grain	Bag	Moisture (% w.b)	R.H (%)	
Corn	jute	12	70	0.9910
	poly	12	70	0.9875
	jute	12	80	0.9962
	poly	12	80	0.9821
	jute	14	80	0.9828
	poly	14	80	0.9919
	jute	12	90	0.9901
	poly	12	90	0.9848
	jute	14	90	0.9925
	poly	14	90	0.9965
Rice	jute	12	70	0.9843
	poly	12	70	0.9954
	jute	12	80	0.9412
	poly	12	80	0.9889
	jute	12	90	0.9965
	poly	12	90	0.9946

Table 16. Values of Parameters in Elovich and Zhabrova's Equation.

Environmental Conditions	Grain	Bag	Initial Moisture (w.b)	A	C	t_o
Temp. = 26.7°C	Corn	Jute	12%	1.245	4.356	30.5
R.H = 70 %		Poly		1.551	6.154	50.5
	Rice	Jute	12%	0.493	1.645	30.5
		Poly		0.446	1.510	30.5
Temp. = 26.7°C	Corn	Jute	12%	1.371	4.760	30.5
R.H = 80%		Poly		0.404	0.998	10.5
		Jute	14%	0.531	1.343	10.5
		Poly		0.549	1.611	15.5
	Rice	Jute	12%	0.464	1.297	15.5
		Poly		0.358	0.981	15.5
Temp. = 26.7°C	Corn	Jute	12%	1.518	5.052	30.0
R.H = 90%		Poly		1.320	4.526	30.0
		Jute	14%	0.508	1.134	15.0
		Poly		0.871	3.086	30.5
	Rice	Jute	12%	0.795	2.567	25.0
		Poly		0.728	2.410	25.5

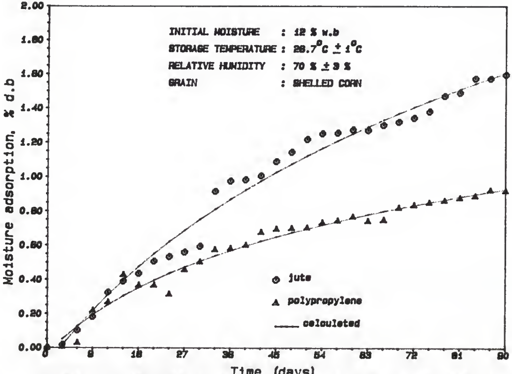


FIGURE 20. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

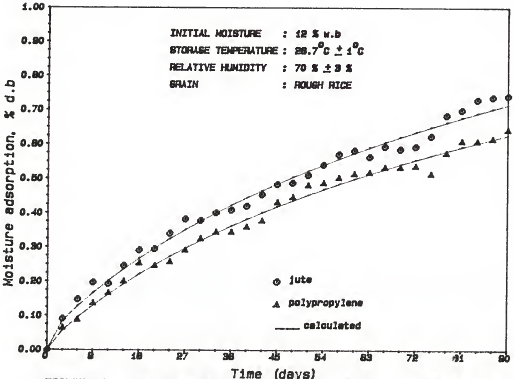


FIGURE 21. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

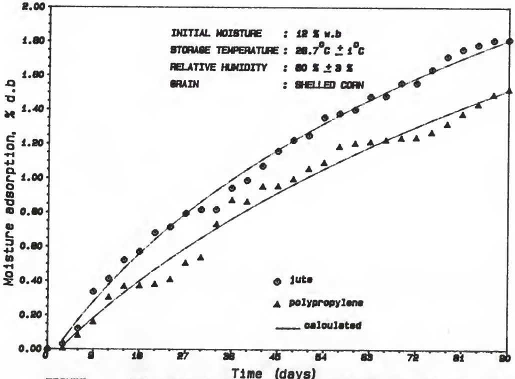


FIGURE 22. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

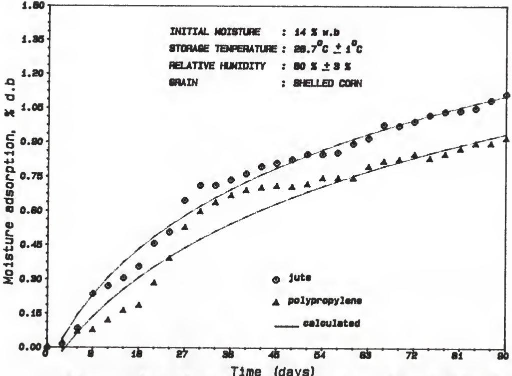


FIGURE 23. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

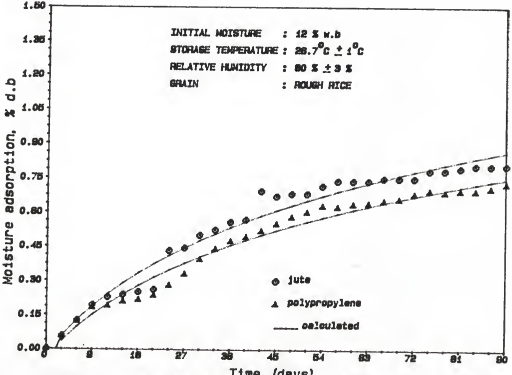


FIGURE 24. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

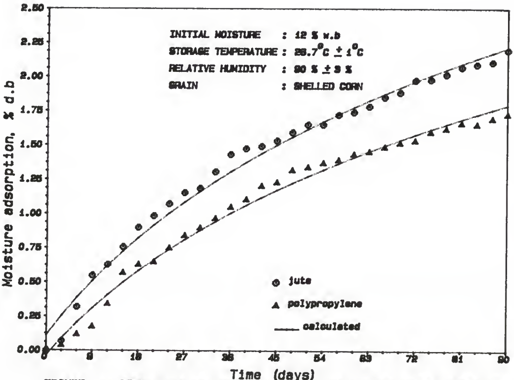


FIGURE 25. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

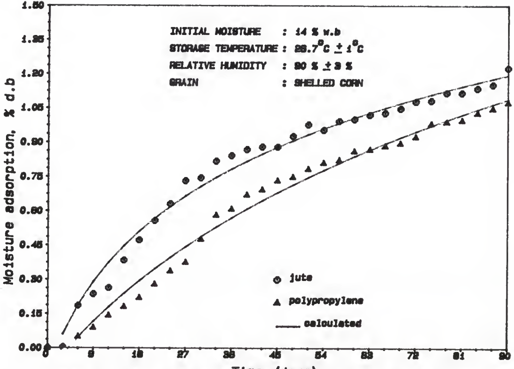


FIGURE 26. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

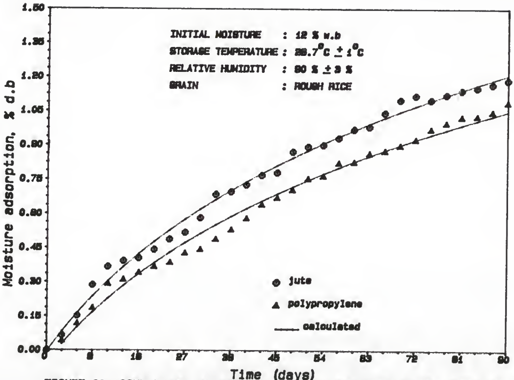


FIGURE 27. COMPARISON OF OBSERVED AND CALCULATED MOISTURE SORPTION RATE OF GRAIN BY USING ELOVICH AND ZHABROVA'S EQUATION.

V. CONLUSIONS

The following conclusions were drawn from this study :

1. Bagged dry grain stored under high relative humidity adsorbs moisture from the environment. Moisture at the surface of both jute and polypropylene bags containing shelled corn and stored for 90 days under 80 % or 90 % relative humidity and 26.7 ^{o}C (80 ^{o}F) increased from an initial moisture of 14 % (w.b) to about 16 % moisture. At this moisture level grains become very prone to insect and fungal deterioration. However, in this environmental condition rough rice did not increase to such a high moisture level. For all the experiments, 90 days was not sufficient time to reach the equilibrium moisture with the corresponding environmental air.
2. The moisture sorption rate of grain in the stack of jute and polypropylene bags depended on the position in the stack. Grain at the surface adsorbed more moisture than the center of the stack or the point in between. In the desorption process shelled corn at the surface desorbed more moisture than the other two positions studied.
3. The relative humidity and initial moisture content of the grain had significant effects on the moisture sorption rate of grain. The adsorption increased with

either decreasing initial moisture or increasing relative humidities.

4. The moisture adsorption rate of shelled corn was greater than that of rough rice.
5. Grain having the same initial moisture adsorbed and desorbed more moisture in jute bags than grain in polypropylene bags stored under same air temperature and relative humidity combinations.
6. The experimental data obtained in this study correlated well with Elovich and Zhabrova's, and Chung's adsorption rate equations.

SUGGESTION FOR FUTURE STUDY

The following recomendations are made for future research :

1. This study did not include any replications because of time constraint. Conduct similar experiments with replications so as to be able to do more elaborate statistical analysis.
2. Study the effects of brokens, fines, and foreign materials in the bagged grain on moisture sorption rate stored under tropical conditions.
3. Extend the period of the experiment and increase grain quantities or stack size in order to get further information on moisture sorption of bagged grain.
4. Study the effects of air temperature on moisture sorption of bagged grain at two or more air temperature levels.
5. Conduct a similar study for milled rice because it is widely stored in warehouses in tropical countries.

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APPENDIX A

Experimental Data

Table A - 1. Moisture Sorption of Shelled Corn at 12 % Initial Moisture in Stack of Jute Bags Stored under 70 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	11.95	12.01	12.02	11.99
3	11.99	12.02	12.02	12.01
6	12.10	12.08	12.07	12.08
9	12.15	12.17	12.14	12.15
12	12.32	12.27	12.25	12.28
15	12.31	12.38	12.34	12.34
18	12.41	12.38	12.36	12.38
21	12.47	12.41	12.44	12.44
24	12.48	12.48	12.45	12.46
27	12.51	12.48	12.47	12.49
30	12.53	12.54	12.48	12.52
33	12.84	12.80	12.76	12.80
36	12.88	12.88	12.80	12.85
39	12.88	12.90	12.82	12.86
42	12.90	12.91	12.83	12.88
45	13.00	12.93	12.93	12.95
48	13.01	13.00	12.99	13.00
51	13.12	13.08	13.02	13.07
54	13.13	13.09	13.07	13.10
57	13.14	13.08	13.09	13.10
60	13.57	13.10	13.09	13.12
63	13.18	13.12	13.07	13.12
66	13.22	13.14	13.10	13.15
69	13.25	13.11	13.14	13.17
72	13.30	13.15	13.13	13.19
75	13.36	13.21	13.12	13.23
78	13.37	13.30	13.21	13.29
81	13.40	13.29	13.26	13.32
84	13.47	13.33	13.31	13.37
87	13.48	13.32	13.35	13.38
90	13.48	13.38	13.34	13.40

[a] Average of 2 moisture readings.

Table A - 2. Moisture Sorption of Shelled Corn at 12 % Initial Moisture in Stack of Polypropylene Bags Stored under 70 % Relative Humidity and 28.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	11.96	11.85	11.85	11.89
3	11.95	11.96	11.92	11.94
6	11.99	11.95	11.95	11.98
9	12.06	12.02	11.94	12.01
12	12.11	12.00	11.99	12.03
15	12.17	12.02	12.00	12.06
18	12.19	12.09	12.05	12.11
21	12.21	12.07	12.03	12.10
24	12.20	12.11	12.03	12.11
27	12.25	12.14	12.04	12.14
30	12.27	12.17	12.08	12.17
33	12.31	12.18	12.08	12.19
36	12.34	12.17	12.06	12.19
39	12.35	12.18	12.08	12.20
42	12.35	12.21	12.10	12.22
45	12.34	12.35	12.11	12.27
48	12.36	12.35	12.13	12.28
51	12.43	12.38	12.12	12.31
54	12.42	12.39	12.14	12.32
57	12.42	12.40	12.17	12.33
60	12.44	12.41	12.17	12.34
63	12.44	12.38	12.21	12.34
66	12.48	12.42	12.19	12.36
69	12.45	12.43	12.19	12.36
72	12.47	12.43	12.18	12.36
75	12.48	12.44	12.12	12.34
78	12.51	12.47	12.20	12.39
81	12.55	12.46	12.26	12.42
84	12.55	12.47	12.25	12.42
87	12.57	12.48	12.26	12.43
90	12.59	12.48	12.29	12.45

[a] Average of 2 moisture readings.

Table A - 3. Moisture Sorption of Shelled Corn at 14 % Initial Moisture in Stack of Jute Bags Stored under 70 % Relative Humidity and 26.7 °C (60 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	13.95	14.00	14.09	14.01
3	14.00	14.00	14.03	14.01
6	13.97	14.00	14.01	13.99
9	13.90	13.96	14.00	13.96
12	13.65	13.96	13.95	13.93
15	13.60	13.69	13.92	13.67
16	13.76	13.76	13.66	13.61
21	13.70	13.67	13.60	13.72
24	13.60	13.66	13.75	13.66
27	13.65	13.66	13.74	13.69
30	13.65	13.67	13.70	13.67
33	13.64	13.66	13.69	13.67
36	13.57	13.55	13.59	13.57
39	13.64	13.63	13.60	13.62
42	13.64	13.65	13.66	13.66
45	13.60	13.63	13.63	13.62
46	13.66	13.70	13.71	13.70
51	13.67	13.70	13.70	13.69
54	13.66	13.71	13.70	13.69
57	13.65	13.72	13.72	13.70
60	13.66	13.72	13.71	13.70
63	13.65	13.72	13.74	13.70
66	13.67	13.71	13.70	13.69
69	13.70	13.72	13.73	13.72
72	13.71	13.75	13.74	13.73
75	13.72	13.76	13.76	13.76
76	13.70	13.77	13.76	13.75
61	13.69	13.77	13.76	13.74
64	13.71	13.76	13.75	13.75
67	13.70	13.76	13.77	13.75
90	13.71	13.77	13.76	13.75

[a] Average of 2 moisture readings.

Table A - 4. Moisture Sorption of Shelled Corn at 14 % Initial Moisture in Stack of Polypropylene Bags Stored under 70 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	14.00	14.03	14.09	14.04
3	13.98	13.99	14.03	14.00
6	13.95	14.00	14.01	13.99
9	13.89	13.94	13.96	13.93
12	13.93	13.93	13.96	13.94
15	13.87	13.93	13.89	13.90
18	13.88	13.94	13.86	13.89
21	13.76	13.86	13.90	13.84
24	13.70	13.78	13.81	13.76
27	13.69	13.79	13.80	13.76
30	13.70	13.71	13.71	13.71
33	13.68	13.70	13.68	13.69
36	13.60	13.71	13.64	13.65
39	13.68	13.73	13.74	13.72
42	13.66	13.70	13.69	13.68
45	13.67	13.71	13.69	13.69
48	13.72	13.74	13.75	13.74
51	13.73	13.73	13.74	13.73
54	13.74	13.74	13.75	13.74
57	13.72	13.74	13.74	13.73
60	13.72	13.72	13.75	13.73
63	13.70	13.75	13.74	13.73
66	13.72	13.75	13.73	13.73
69	13.75	13.74	13.76	13.75
72	13.74	13.73	13.76	13.74
75	13.75	13.75	13.76	13.75
78	13.76	13.77	13.76	13.76
81	13.77	13.77	13.78	13.77
84	13.75	13.78	13.78	13.78
87	13.75	13.76	13.77	13.76
90	13.76	13.76	13.77	13.76

[a] Average of 2 moisture readings.

Table A - 5. Moisture Sorption of Rough Rice at 12 % Initial Moisture in Stack of Jute Bags Stored under 70 % Relative Humidity and 28.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	11.90	11.88	11.87	11.88
3	11.96	11.97	11.96	11.98
8	12.01	12.03	12.00	12.01
9	12.10	12.04	12.03	12.08
12	12.11	12.05	12.00	12.05
15	12.18	12.08	12.04	12.10
18	12.27	12.10	12.05	12.14
21	12.29	12.10	12.04	12.14
24	12.30	12.17	12.08	12.18
27	12.35	12.19	12.12	12.22
30	12.35	12.20	12.10	12.22
33	12.37	12.21	12.13	12.24
36	12.38	12.22	12.13	12.24
39	12.38	12.24	12.14	12.25
42	12.39	12.30	12.16	12.28
45	12.39	12.37	12.17	12.31
48	12.40	12.38	12.16	12.31
51	12.44	12.39	12.17	12.33
54	12.47	12.43	12.18	12.36
57	12.49	12.49	12.18	12.39
60	12.51	12.48	12.20	12.40
63	12.49	12.45	12.20	12.38
66	12.52	12.46	12.24	12.41
69	12.52	12.47	12.21	12.40
72	12.51	12.48	12.23	12.41
75	12.55	12.47	12.28	12.43
78	12.86	12.51	12.29	12.49
81	12.65	12.55	12.30	12.50
84	12.67	12.55	12.38	12.53
87	12.88	12.57	12.35	12.53
90	12.70	12.59	12.32	12.54

[a] Average of 2 moisture readings.

Table A - 6. Moisture Sorption of Shelled Corn at 12 % Initial Moisture in Stack of Polypropylene Bags Stored under 70 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture contnet (% wet basis)[a]			
	Surface	In between	Center	Average
0	11.96	11.85	11.85	11.89
3	11.95	11.96	11.92	11.94
6	11.99	11.95	11.95	11.96
9	12.06	12.02	11.94	12.01
12	12.11	12.00	11.99	12.03
15	12.17	12.02	12.00	12.06
18	12.19	12.09	12.05	12.11
21	12.21	12.07	12.03	12.10
24	12.20	12.11	12.03	12.11
27	12.25	12.14	12.04	12.14
30	12.27	12.17	12.08	12.17
33	12.31	12.18	12.08	12.19
36	12.34	12.17	12.06	12.19
39	12.35	12.18	12.08	12.20
42	12.35	12.21	12.10	12.22
45	12.34	12.35	12.11	12.27
48	12.36	12.35	12.13	12.28
51	12.43	12.38	12.12	12.31
54	12.42	12.39	12.14	12.32
57	12.42	12.40	12.17	12.33
60	12.44	12.41	12.17	12.34
63	12.44	12.38	12.21	12.34
66	12.46	12.42	12.19	12.36
69	12.45	12.43	12.19	12.36
72	12.47	12.43	12.18	12.36
75	12.46	12.44	12.12	12.34
78	12.51	12.47	12.20	12.39
81	12.55	12.46	12.26	12.42
84	12.55	12.47	12.25	12.42
87	12.57	12.48	12.26	12.43
90	12.59	12.46	12.29	12.45

[a] Average of 2 moisture readings.

Table A - 7. Moisture Sorption of Shelled Corn at 12 % Initial Moisture in Stack of Jute Bags Stored under 80 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	12.04	12.03	12.03	12.03
3	12.10	12.04	12.04	12.08
6	12.22	12.11	12.09	12.14
9	12.40	12.32	12.27	12.33
12	12.44	12.38	12.37	12.40
15	12.62	12.47	12.39	12.49
18	12.64	12.53	12.44	12.54
21	12.79	12.60	12.51	12.63
24	12.89	12.59	12.51	12.66
27	13.00	12.67	12.53	12.73
30	13.02	12.61	12.63	12.75
33	13.20	12.58	12.48	12.75
36	13.30	12.76	12.53	12.86
39	13.38	12.79	12.54	12.90
42	13.39	12.83	12.71	12.98
45	13.38	12.98	12.80	13.05
48	13.45	13.00	12.88	13.11
51	13.50	13.00	12.90	13.13
54	13.55	13.14	12.99	13.23
57	13.55	13.12	13.07	13.25
60	13.55	13.15	13.10	13.27
63	13.57	13.25	13.18	13.33
66	13.62	13.23	13.16	13.34
69	13.70	13.28	13.23	13.40
72	13.69	13.28	13.24	13.40
75	13.75	13.37	13.30	13.47
78	13.74	13.48	13.40	13.54
81	13.73	13.57	13.43	13.58
84	13.81	13.57	13.42	13.60
87	13.80	13.58	13.49	13.62
90	13.88	13.65	13.35	13.63

[a] Average of 2 moisture readings.

Table A - 8. Moisture Sorption of Shelled Corn at 12 % Initial Moisture in Stack of Polypropylene Bags Stored under 80 % Relative Humidity and 28.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	12.06	12.00	11.98	12.01
3	12.01	12.01	12.01	12.01
6	12.08	12.10	12.07	12.08
9	12.18	12.22	12.08	12.15
12	12.42	12.30	12.12	12.28
15	12.43	12.35	12.23	12.34
18	12.43	12.36	12.23	12.34
21	12.42	12.36	12.26	12.35
24	12.40	12.40	12.32	12.37
27	12.51	12.46	12.40	12.46
30	12.51	12.50	12.45	12.49
33	12.75	12.68	12.54	12.66
36	12.89	12.78	12.87	12.78
39	12.85	12.78	12.89	12.77
42	12.91	12.89	12.75	12.85
45	12.93	12.89	12.74	12.85
48	12.93	12.93	12.81	12.89
51	12.99	12.97	12.87	12.94
54	13.02	12.98	12.92	12.97
57	13.14	13.12	12.91	13.06
60	13.14	13.10	12.98	13.07
63	13.14	13.10	13.00	13.08
66	13.14	13.14	12.99	13.09
69	13.17	13.15	12.98	13.10
72	13.16	13.14	13.01	13.10
75	13.21	13.17	13.01	13.13
78	13.28	13.19	13.05	13.17
81	13.33	13.24	13.10	13.22
84	13.34	13.30	13.18	13.27
87	13.39	13.35	13.23	13.32
90	13.42	13.37	13.28	13.35

[a] Average of 2 moisture readings.

Table A - 9. Moisture Sorption of Shelled Corn at 14 % Initial Moisture in Stack of Jute Bags Stored under 80 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	14.01	13.98	13.98	13.99
3	14.05	13.99	13.97	14.00
6	14.15	14.04	14.00	14.03
9	14.21	14.15	14.14	14.07
12	14.37	14.15	14.15	14.09
15	14.37	14.16	14.17	14.10
18	14.41	14.21	14.19	14.18
21	14.74	14.20	14.21	14.38
24	14.81	14.27	14.20	14.43
27	15.00	14.41	14.38	14.59
30	15.08	14.44	14.35	14.62
33	15.07	14.48	14.33	14.63
36	15.03	14.48	14.36	14.62
39	15.11	14.50	14.40	14.67
42	15.10	14.50	14.42	14.67
45	15.14	14.50	14.44	14.67
48	15.14	14.51	14.45	14.70
51	15.20	14.50	14.48	14.73
54	15.18	14.51	14.46	14.72
57	15.20	14.50	14.48	14.73
60	15.21	14.55	14.50	14.75
63	15.25	14.56	14.53	14.71
66	15.28	14.61	14.60	14.72
69	15.27	14.63	14.58	14.73
72	15.28	14.65	14.60	14.70
75	15.28	14.68	14.64	14.72
78	15.29	14.66	14.69	14.71
81	15.30	14.67	14.68	14.72
84	15.30	14.69	14.69	14.73
87	15.35	14.73	14.69	14.76
90	15.43	14.72	14.69	14.68

[a] Average of 2 moisture readings.

Table A - 10. Moisture Sorption of Shelled Corn at 14 % Initial Moisture in Stack of Polypropylne Bags Stored under 80 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	13.99	13.94	14.00	13.98
3	14.00	14.01	13.98	14.00
6	14.07	14.04	14.00	14.04
9	14.07	14.03	14.03	14.04
12	14.13	14.07	14.05	14.08
15	14.24	14.13	14.05	14.14
18	14.31	14.14	14.07	14.17
21	14.40	14.17	14.11	14.23
24	14.48	14.17	14.19	14.28
27	14.54	14.25	14.23	14.34
30	14.59	14.30	14.38	14.42
33	14.60	14.35	14.34	14.43
36	14.64	14.40	14.40	14.48
39	14.68	14.43	14.40	14.50
42	14.72	14.44	14.44	14.53
45	14.75	14.47	14.45	14.56
48	14.77	14.50	14.41	14.56
51	14.81	14.49	14.44	14.58
54	14.87	14.49	14.46	14.61
57	14.91	14.50	14.44	14.62
60	14.93	14.47	14.47	14.62
63	14.99	14.52	14.47	14.66
66	15.03	14.53	14.48	14.68
69	15.04	14.54	14.48	14.69
72	15.06	14.56	14.50	14.71
75	15.00	14.58	14.51	14.69
78	15.04	14.55	14.53	14.71
81	15.05	14.58	14.57	14.73
84	15.08	14.57	14.59	14.75
87	15.05	14.60	14.59	14.75
90	15.11	14.60	14.62	14.77

[a] Average of 2 moisture readings.

Table A - 11. Moisture Sorption of Rough Rice at 12 % Initial Moisture in Stack of Jute Bags Stored under 80 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	12.01	12.00	12.00	12.00
3	12.08	12.04	12.03	12.05
6	12.17	12.09	12.06	12.11
9	12.31	12.13	12.08	12.17
12	12.40	12.13	12.07	12.20
15	12.41	12.13	12.10	12.21
18	12.40	12.14	12.11	12.22
21	12.39	12.21	12.10	12.23
24	12.50	12.34	12.29	12.38
27	12.69	12.33	12.31	12.39
30	12.75	12.34	12.29	12.44
33	12.80	12.33	12.25	12.46
36	12.85	12.32	12.29	12.49
39	12.86	12.34	12.30	12.50
42	12.90	12.55	12.38	12.61
45	12.89	12.50	12.39	12.59
48	12.90	12.53	12.36	12.60
51	12.89	12.54	12.37	12.60
54	12.93	12.58	12.38	12.63
57	12.93	12.59	12.42	12.65
60	12.92	12.57	12.46	12.65
63	12.98	12.60	12.38	12.65
66	13.00	12.60	12.38	12.66
69	13.01	12.63	12.35	12.66
72	13.02	12.64	12.33	12.66
75	13.00	12.64	12.44	12.69
78	13.00	12.63	12.44	12.69
81	13.00	12.66	12.45	12.70
84	13.02	12.67	12.43	12.71
87	13.01	12.68	12.45	12.71
90	13.02	12.64	12.48	12.73

[a] Average of 2 moisture readings.

Table A - 12. Moisture Sorption of Rough Rice at 12 % Initial Moisture in Stack of Polypropylene Bags Stored under 70 % Relative Humidity and 26.7 ^{o}C (80 ^{o}F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	11.98	12.00	12.02	12.00
3	12.08	12.04	12.03	12.05
6	12.17	12.09	12.06	12.11
9	12.31	12.13	12.06	12.17
12	12.40	12.13	12.07	12.20
15	12.41	12.13	12.10	12.21
18	12.29	12.09	12.10	12.16
21	12.27	12.15	12.11	12.18
24	12.27	12.10	12.10	12.16
27	12.38	12.31	12.27	12.32
30	12.48	12.40	12.26	12.38
33	12.48	12.42	12.30	12.40
36	12.56	12.40	12.30	12.42
39	12.56	12.41	12.29	12.42
42	12.72	12.49	12.32	12.51
45	12.70	12.50	12.34	12.51
48	12.69	12.51	12.33	12.51
51	12.70	12.50	12.30	12.50
54	12.69	12.53	12.30	12.51
57	12.68	12.54	12.34	12.52
60	12.70	12.55	12.36	12.54
63	12.67	12.54	12.21	12.47
66	12.71	12.50	12.25	12.49
69	12.77	12.50	12.27	12.51
72	12.78	12.51	12.30	12.53
75	12.79	12.50	12.32	12.54
78	12.76	12.53	12.38	12.56
81	12.77	12.54	12.39	12.57
84	12.78	12.55	12.37	12.57
87	12.78	12.55	12.38	12.57
90	12.76	12.47	12.36	12.53

[a] Average of 2 moisture readings.

Table A - 13. Moisture Sorption of Shelled Corn a 12 % Initial Moisture in Stack of Jute Bags Stored under 90 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	12.01	11.98	12.03	12.01
3	12.10	12.07	12.03	12.07
6	12.42	12.27	12.17	12.29
9	12.57	12.48	12.42	12.49
12	12.68	12.59	12.41	12.58
15	12.88	12.57	12.57	12.87
18	12.90	12.83	12.68	12.80
21	13.10	12.89	12.83	12.87
24	13.25	12.82	12.78	12.95
27	13.24	12.94	12.88	13.02
30	13.33	12.94	12.88	13.05
33	13.47	13.00	13.00	13.16
36	13.53	13.17	13.10	13.27
39	13.50	13.20	13.21	13.30
42	13.56	13.21	13.19	13.32
45	13.86	13.20	13.21	13.38
48	13.65	13.33	13.25	13.41
51	13.75	13.30	13.33	13.48
54	13.74	13.30	13.34	13.46
57	13.84	13.36	13.37	13.52
60	13.88	13.36	13.38	13.54
63	13.96	13.40	13.37	13.58
66	14.00	13.44	13.47	13.84
69	13.99	13.51	13.50	13.67
72	14.05	13.66	13.53	13.75
75	14.05	13.68	13.52	13.75
78	14.15	13.68	13.52	13.78
81	14.16	13.66	13.67	13.83
84	14.20	13.85	13.89	13.85
87	14.19	13.70	13.70	13.86
90	14.22	13.81	13.79	13.94

[a] Average of 2 moisture readings.

Table A - 14. Moisture Sorption of Shelled Corn at 12 % Initial Moisture in Stack of Polypropylene Bags Stored under 90 % Relative Humidity and 28.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	11.99	12.01	12.01	12.00
3	12.05	12.05	12.01	12.04
6	12.15	12.07	12.10	12.11
9	12.25	12.11	12.11	12.16
12	12.38	12.28	12.25	12.30
15	12.58	12.48	12.45	12.50
18	12.61	12.52	12.54	12.56
21	12.68	12.52	12.54	12.57
24	12.76	12.62	12.61	12.68
27	12.89	12.66	12.68	12.74
30	12.96	12.71	12.71	12.79
33	13.00	12.76	12.80	12.85
36	13.10	12.86	12.82	12.93
39	13.12	12.90	12.91	12.98
42	13.20	13.00	12.99	13.06
45	13.28	13.00	13.00	13.09
48	13.30	13.10	13.09	13.16
51	13.32	13.12	13.11	13.18
54	13.38	13.15	13.10	13.21
57	13.40	13.20	13.09	13.23
60	13.40	13.25	13.15	13.27
63	13.41	13.27	13.17	13.28
66	13.50	13.30	13.14	13.31
69	13.53	13.33	13.16	13.34
72	13.55	13.31	13.20	13.35
75	13.66	13.31	13.26	13.41
78	13.67	13.34	13.28	13.43
81	13.70	13.39	13.31	13.47
84	13.68	13.41	13.29	13.46
87	13.71	13.46	13.32	13.50
90	13.72	13.45	13.40	13.52

[a] Average of 2 moisture readings.

Table A - 15. Moisture Sorption of Shelled Corn at 14 % Initial Moisture in Stack of Jute Bags Stored under 90 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	14.04	14.00	14.03	14.02
3	14.06	14.00	14.02	14.03
6	14.25	14.18	14.12	14.18
9	14.31	14.19	14.18	14.23
12	14.40	14.18	14.17	14.25
15	14.49	14.30	14.27	14.35
18	14.82	14.33	14.34	14.43
21	14.78	14.40	14.33	14.50
24	14.86	14.41	14.43	14.57
27	15.11	14.42	14.43	14.85
30	15.16	14.40	14.43	14.66
33	15.28	14.43	14.49	14.73
36	15.27	14.49	14.48	14.75
39	15.34	14.50	14.47	14.77
42	15.38	14.51	14.47	14.78
45	15.36	14.51	14.47	14.78
48	15.37	14.80	14.49	14.82
51	15.38	14.66	14.55	14.86
54	15.36	14.80	14.57	14.84
57	15.42	14.83	14.58	14.88
60	15.43	14.64	14.58	14.88
63	15.48	14.65	14.59	14.90
66	15.48	14.64	14.82	14.91
69	15.48	14.66	14.63	14.92
72	15.50	14.70	14.65	14.95
75	15.49	14.72	14.85	14.95
78	15.52	14.73	14.70	14.98
81	15.55	14.72	14.68	14.98
84	15.60	14.72	14.68	15.00
87	15.83	14.73	14.68	15.01
90	15.79	14.74	14.70	15.08

[a] Average of 2 moisture readings.

Table A - 16. Moisture Sorption of Shelled Corn at 14 % Initial Moisture in Stack of Polypropylene Bags Stored under 90 % Relative Humidity 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	14.00	14.03	14.02	14.02
3	14.02	13.99	14.00	14.00
6	14.15	14.03	14.00	14.08
9	14.20	14.05	14.03	14.09
12	14.25	14.10	14.07	14.14
15	14.32	14.11	14.09	14.17
18	14.32	14.18	14.12	14.21
21	14.45	14.20	14.12	14.26
24	14.55	14.21	14.16	14.31
27	14.60	14.25	14.17	14.34
30	14.65	14.33	14.30	14.43
33	14.78	14.38	14.39	14.52
36	14.80	14.39	14.43	14.54
39	14.86	14.47	14.45	14.59
42	14.90	14.48	14.46	14.61
45	14.91	14.56	14.47	14.65
48	14.98	14.55	14.47	14.66
51	15.00	14.57	14.50	14.69
54	15.05	14.57	14.52	14.71
57	15.06	14.60	14.51	14.72
60	15.10	14.62	14.55	14.76
63	15.09	14.63	14.57	14.76
66	15.11	14.64	14.58	14.78
69	15.15	14.62	14.59	14.79
72	15.18	14.64	14.61	14.81
75	15.28	14.67	14.63	14.86
78	15.30	14.68	14.62	14.87
81	15.32	14.68	14.62	14.87
84	15.38	14.69	14.65	14.90
87	15.40	14.70	14.65	14.92
90	15.48	14.69	14.65	14.94

[a] Average of 2 moisture readings.

Table A - 17. Moisture Sorption of Rough Rice at 12 % Initial Moisture in Stack of Jute Bags Stored under 90 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	12.00	12.02	11.98	12.00
3	12.08	12.08	12.03	12.08
8	12.19	12.10	12.11	12.13
9	12.38	12.21	12.19	12.25
12	12.44	12.33	12.20	12.32
15	12.47	12.32	12.25	12.35
18	12.47	12.31	12.29	12.38
21	12.50	12.33	12.34	12.39
24	12.61	12.38	12.32	12.43
27	12.86	12.40	12.31	12.48
30	12.78	12.41	12.35	12.51
33	12.88	12.53	12.40	12.60
36	12.90	12.55	12.39	12.81
39	12.95	12.53	12.44	12.84
42	13.00	12.55	12.48	12.68
45	13.00	12.58	12.50	12.69
48	13.05	12.67	12.58	12.77
51	13.10	12.68	12.60	12.79
54	13.09	12.70	12.59	12.79
57	13.15	12.71	12.60	12.82
80	13.15	12.77	12.64	12.85
63	13.13	12.80	12.66	12.86
66	13.16	12.81	12.78	12.92
69	13.18	12.90	12.82	12.97
72	13.19	12.91	12.85	12.98
75	13.18	12.90	12.82	12.97
78	13.25	12.91	12.80	12.99
81	13.29	12.92	12.80	13.00
84	13.30	12.93	12.81	13.01
87	13.37	12.91	12.80	13.03
90	13.40	12.93	12.80	13.04

[a] Average of 2 moisture readings.

Table A - 18. Moisture Sorption of Rough Rice at 12 % Initial Moisture in Stack of Polypropylene Bags Stored under 90 % Relative Humidity and 26.7 °C (80 °F).

Days	Moisture Content (% Wet Basis)[a]			
	Surface	In between	Center	Average
0	11.98	11.97	12.01	11.99
3	12.03	12.03	12.01	12.02
6	12.14	12.08	12.05	12.09
9	12.24	12.10	12.11	12.15
12	12.31	12.21	12.21	12.24
15	12.33	12.25	12.20	12.26
18	12.35	12.27	12.24	12.29
21	12.40	12.26	12.27	12.31
24	12.39	12.30	12.29	12.33
27	12.45	12.35	12.29	12.38
30	12.47	12.36	12.30	12.38
33	12.50	12.40	12.35	12.42
36	12.57	12.39	12.40	12.45
39	12.67	12.43	12.39	12.50
42	12.76	12.44	12.45	12.55
45	12.80	12.50	12.43	12.58
48	12.79	12.54	12.49	12.61
51	12.88	12.57	12.50	12.65
54	12.93	12.56	12.49	12.66
57	12.99	12.60	12.54	12.71
60	12.99	12.57	12.58	12.71
63	13.03	12.61	12.60	12.75
66	13.05	12.63	12.59	12.76
69	13.10	12.66	12.57	12.78
72	13.10	12.70	12.60	12.80
75	13.10	12.76	12.66	12.84
78	13.14	12.80	12.65	12.86
81	13.17	12.79	12.70	12.89
84	13.18	12.80	12.69	12.89
87	13.21	12.80	12.71	12.91
90	13.25	12.84	12.74	12.94

[a] Average of 2 moisture readings.

APPENDIX B

Comparison of Calculated and Experimental Moisture Sorption Rate Data Using Chung's Equation.

Table B - 1. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Chung's Equation in Stack of Jute Bags at 12 % Initial Moisture Content and 26.7 °C (80 °F).

Days	Relative Humidity					
	70 %		80 %		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	0.0008	0.0000	0.0008	0.0000	0.0008
3	0.0087	0.0583	0.0068	0.0310	0.0080	0.0390
6	0.0467	0.1006	0.0285	0.0518	0.0375	0.0588
9	0.0831	0.1391	0.0738	0.0708	0.0649	0.0710
12	0.1490	0.1750	0.0905	0.0885	0.0744	0.0834
15	0.1788	0.2088	0.1147	0.1055	0.0898	0.0946
18	0.1995	0.2408	0.1256	0.1218	0.1065	0.1049
21	0.2328	0.2711	0.1498	0.1376	0.1170	0.1145
24	0.2448	0.3001	0.1574	0.1529	0.1274	0.1237
27	0.2570	0.3277	0.1750	0.1678	0.1370	0.1323
30	0.2728	0.3541	0.1800	0.1823	0.1411	0.1406
33	0.4218	0.3793	0.1800	0.1984	0.1557	0.1486
36	0.4499	0.4035	0.2078	0.2102	0.1708	0.1563
39	0.4535	0.4286	0.2179	0.2237	0.1759	0.1638
42	0.4640	0.4488	0.2365	0.2369	0.1782	0.1710
45	0.5028	0.4700	0.2559	0.2498	0.1832	0.1781
48	0.5275	0.4904	0.2703	0.2624	0.1906	0.1849
51	0.5829	0.5099	0.2763	0.2748	0.1975	0.1916
54	0.5789	0.5287	0.3000	0.2869	0.1975	0.1981
57	0.5808	0.5467	0.3051	0.2988	0.2062	0.2045
60	0.5895	0.5640	0.3103	0.3104	0.2085	0.2107
63	0.5877	0.5808	0.3273	0.3219	0.2136	0.2168
66	0.6019	0.5965	0.3281	0.3331	0.2219	0.2228
69	0.6108	0.6118	0.3451	0.3441	0.2261	0.2287
72	0.6214	0.6285	0.3451	0.3548	0.2372	0.2344
75	0.6391	0.6408	0.3631	0.3654	0.2377	0.2401
78	0.6618	0.6542	0.3802	0.3758	0.2423	0.2457
81	0.6907	0.6673	0.3896	0.3860	0.2488	0.2512
84	0.7299	0.6798	0.3956	0.3960	0.2511	0.2566
87	0.7299	0.6919	0.4018	0.4059	0.2534	0.2619
90	0.7406	0.7035	0.4025	0.4155	0.2641	0.2671

Table B - 2. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Chung's Equation in Stack of Polypropylene Bags at 12 % Initial Moisture Content and 26.7 ^{o}C (60 ^{o}F).

Days	Relative Humidity					
	70 %		60%		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	0.0006	0.0000	0.0006	0.0000	0.0006
3	0.0035	0.0557	0.0006	0.0190	0.0045	0.0241
6	0.0140	0.0639	0.0173	0.0340	0.0136	0.0365
9	0.1015	0.1072	0.0346	0.0462	0.0205	0.0469
12	0.1243	0.1260	0.0660	0.0619	0.0402	0.0563
15	0.1961	0.1471	0.0601	0.0752	0.0672	0.0650
16	0.1700	0.1649	0.0609	0.0663	0.0744	0.0732
21	0.1700	0.1616	0.0626	0.1010	0.0766	0.0611
24	0.1454	0.1975	0.0692	0.1135	0.0666	0.0666
27	0.2122	0.2127	0.1099	0.1257	0.0997	0.0959
30	0.2334	0.2273	0.1174	0.1377	0.1065	0.1029
33	0.2669	0.2414	0.1599	0.1495	0.1146	0.1096
36	0.2705	0.2549	0.1906	0.1611	0.1246	0.1164
39	0.2793	0.2660	0.1691	0.1726	0.1315	0.1230
42	0.3147	0.2607	0.2064	0.1636	0.1433	0.1294
45	0.3235	0.2931	0.2092	0.1949	0.1465	0.1356
46	0.3253	0.3051	0.2164	0.2056	0.1570	0.1417
51	0.3270	0.3167	0.2319	0.2165	0.1597	0.1476
54	0.3412	0.3261	0.2394	0.2271	0.1634	0.1537
57	0.3465	0.3391	0.2605	0.2375	0.1662	0.1595
60	0.3571	0.3499	0.2647	0.2477	0.1712	0.1653
63	0.3446	0.3604	0.2664	0.2578	0.1735	0.1709
66	0.3463	0.3707	0.2669	0.2676	0.1776	0.1765
69	0.3620	0.3606	0.2714	0.2776	0.1613	0.1620
72	0.3691	0.3906	0.2723	0.2672	0.1631	0.1674
75	0.3962	0.4002	0.2790	0.2966	0.1909	0.1926
76	0.4015	0.4097	0.2900	0.3061	0.1937	0.1961
61	0.4066	0.4169	0.3026	0.3154	0.1966	0.2033
64	0.4140	0.4279	0.3153	0.3245	0.1976	0.2065
67	0.4300	0.4367	0.3260	0.3335	0.2029	0.2136
90	0.4261	0.4454	0.3346	0.3424	0.2066	0.2166

Table B - 3. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Chung's Equation in Stack of Jute Bags at 14 % Initial Moisture Content and 26.7 ^{o}C (80 ^{o}F).

Days	Relative Humidity			
	80 %		90 %	
	ex.	cal.	ex.	cal.
0	0.0000	0.0006	0.0000	0.0006
3	0.0068	0.0624	0.0007	0.0349
6	0.0378	0.0951	0.0310	0.0499
9	0.0912	0.1225	0.0394	0.0617
12	0.1205	0.1470	0.0439	0.0717
15	0.1257	0.1695	0.0640	0.0808
18	0.1447	0.1905	0.0790	0.0887
21	0.2035	0.2103	0.0933	0.0963
24	0.2281	0.2291	0.1057	0.1033
27	0.3112	0.2470	0.1227	0.1100
30	0.3286	0.2642	0.1246	0.1164
33	0.3304	0.2807	0.1371	0.1224
36	0.3286	0.2968	0.1410	0.1283
39	0.3530	0.3119	0.1458	0.1339
42	0.3547	0.3268	0.1475	0.1393
45	0.3652	0.3411	0.1475	0.1445
48	0.3687	0.3551	0.1554	0.1496
51	0.3827	0.3686	0.1640	0.1546
54	0.3775	0.3817	0.1600	0.1594
57	0.3827	0.3944	0.1666	0.1641
60	0.3987	0.4068	0.1679	0.1687
63	0.4106	0.4189	0.1712	0.1732
66	0.4369	0.4307	0.1725	0.1775
69	0.4352	0.4421	0.1758	0.1818
72	0.4439	0.4532	0.1811	0.1860
75	0.4562	0.4641	0.1817	0.1902
78	0.4632	0.4747	0.1876	0.1942
81	0.4649	0.4851	0.1876	0.1982
84	0.4702	0.4952	0.1909	0.2021
87	0.4860	0.5050	0.1936	0.2060
90	0.4983	0.5147	0.2081	0.2098

Table B - 4. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Chung's Equation in Stack of Poly--propylene Bags at 14 % Initial Moisture Content and 26.7 °C (80 °F).

Days	Relative Humidity			
	80 %		90 %	
	ex.	cal.	ex.	cal.
0	0.0000	0.0006	0.0000	0.0008
3	0.0102	0.0332	0.0026	0.0121
6	0.0307	0.0555	0.0084	0.0205
9	0.0341	0.0757	0.0148	0.0282
12	0.0546	0.0947	0.0238	0.0358
15	0.0837	0.1128	0.0303	0.0428
18	0.1008	0.1302	0.0367	0.0497
21	0.1282	0.1470	0.0464	0.0565
24	0.1557	0.1632	0.0561	0.0632
27	0.1866	0.1790	0.0628	0.0698
30	0.2282	0.1944	0.0795	0.0763
33	0.2330	0.2094	0.0971	0.0826
36	0.2589	0.2240	0.1018	0.0889
39	0.2676	0.2382	0.1120	0.0951
42	0.2865	0.2521	0.1159	0.1013
45	0.2988	0.2657	0.1225	0.1074
48	0.3003	0.2790	0.1251	0.1134
51	0.3107	0.2920	0.1310	0.1193
54	0.3248	0.3047	0.1355	0.1252
57	0.3297	0.3171	0.1375	0.1311
60	0.3332	0.3293	0.1441	0.1368
63	0.3522	0.3413	0.1454	0.1426
66	0.3626	0.3530	0.1480	0.1482
69	0.3661	0.3645	0.1500	0.1539
72	0.3765	0.3757	0.1545	0.1594
75	0.3678	0.3867	0.1644	0.1650
78	0.3765	0.3975	0.1657	0.1704
81	0.3869	0.4081	0.1670	0.1759
84	0.3973	0.4185	0.1722	0.1813
87	0.3973	0.4287	0.1755	0.1866
90	0.4077	0.4387	0.1801	0.1919

Table B - 5. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Rough Rice Using Chung's Equation in Stack of Jute Bags at 12 % Initial Moisture Content and 26.7 ^{o}C (80 ^{o}F).

Days	Relative Humidity					
	70 %		80 %		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	0.0006	0.0000	0.0006	0.0000	0.0006
3	0.0631	0.0639	0.0177	0.0398	0.0103	0.0237
6	0.1028	0.0965	0.0390	0.0582	0.0243	0.0354
9	0.1369	0.1236	0.0604	0.0729	0.0462	0.0452
12	0.1342	0.1477	0.0710	0.0858	0.0591	0.0540
15	0.1712	0.1697	0.0746	0.0975	0.0634	0.0620
18	0.2029	0.1903	0.0782	0.1083	0.0652	0.0696
21	0.2055	0.2096	0.0817	0.1184	0.0713	0.0768
24	0.2373	0.2278	0.1353	0.1279	0.0787	0.0837
27	0.2664	0.2453	0.1388	0.1370	0.0838	0.0903
30	0.2838	0.2620	0.1567	0.1458	0.0940	0.0967
33	0.2796	0.2780	0.1839	0.1542	0.1106	0.1030
36	0.2849	0.2934	0.1748	0.1623	0.1124	0.1090
39	0.2928	0.3083	0.1782	0.1701	0.1174	0.1149
42	0.3187	0.3226	0.2177	0.1777	0.1241	0.1207
45	0.3379	0.3365	0.2105	0.1851	0.1260	0.1264
48	0.3406	0.3500	0.2141	0.1923	0.1408	0.1319
51	0.3585	0.3631	0.2141	0.1994	0.1445	0.1373
54	0.3777	0.3758	0.2249	0.2082	0.1457	0.1427
57	0.3990	0.3881	0.2321	0.2130	0.1507	0.1479
60	0.4070	0.4002	0.2321	0.2195	0.1562	0.1531
63	0.3937	0.4118	0.2321	0.2260	0.1588	0.1582
66	0.4150	0.4232	0.2357	0.2323	0.1686	0.1632
69	0.4096	0.4343	0.2357	0.2385	0.1730	0.1682
72	0.4150	0.4451	0.2357	0.2446	0.1754	0.1730
75	0.4362	0.4557	0.2485	0.2506	0.1779	0.1779
78	0.4788	0.4660	0.2485	0.2564	0.1817	0.1828
81	0.4894	0.4760	0.2501	0.2622	0.1847	0.1873
84	0.5108	0.4858	0.2537	0.2679	0.1886	0.1920
87	0.5181	0.4954	0.2537	0.2735	0.1891	0.1965
90	0.5188	0.5048	0.2537	0.2790	0.1922	0.2011

Table B - 6. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Rough Rice Using Chung's Equation in Stack of Polypropylene Bags at 12 % Initial Moisture Content and 26.7 ^{o}C (80 ^{o}F).

Days	Relative Humidity					
	70 %		80 %		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	0.0006	0.0000	0.0006	0.0000	0.0006
3	0.0448	0.0507	0.0177	0.0355	0.0067	0.0150
6	0.0606	0.0777	0.0390	0.0509	0.0168	0.0238
9	0.0950	0.1006	0.0604	0.0630	0.0297	0.0315
12	0.1161	0.1211	0.0710	0.0734	0.0467	0.0386
15	0.1399	0.1401	0.0746	0.0827	0.0498	0.0453
18	0.1770	0.1579	0.0588	0.0912	0.0546	0.0518
21	0.1716	0.1746	0.0639	0.0990	0.0589	0.0581
24	0.1796	0.1909	0.0566	0.1064	0.0620	0.0642
27	0.2034	0.2063	0.1138	0.1134	0.0667	0.0701
30	0.2273	0.2212	0.1353	0.1201	0.0711	0.0759
33	0.2405	0.2356	0.1424	0.1264	0.0764	0.0816
36	0.2405	0.2495	0.1496	0.1326	0.0852	0.0872
39	0.2511	0.2629	0.1496	0.1385	0.0931	0.0927
42	0.2645	0.2760	0.1818	0.1442	0.1029	0.0981
45	0.3016	0.2887	0.1818	0.1497	0.1078	0.1035
48	0.3122	0.3010	0.1818	0.1551	0.1133	0.1088
51	0.3362	0.3131	0.1782	0.1603	0.1213	0.1140
54	0.3415	0.3246	0.1818	0.1654	0.1232	0.1191
57	0.3521	0.3363	0.1854	0.1704	0.1324	0.1242
60	0.3601	0.3474	0.1926	0.1752	0.1330	0.1292
63	0.3627	0.3584	0.1674	0.1800	0.1392	0.1342
66	0.3735	0.3690	0.1746	0.1846	0.1410	0.1391
69	0.3735	0.3795	0.1818	0.1892	0.1447	0.1440
72	0.3761	0.3897	0.1890	0.1936	0.1490	0.1488
75	0.3601	0.3997	0.1926	0.1980	0.1564	0.1536
78	0.4027	0.4095	0.1997	0.2023	0.1607	0.1583
81	0.4267	0.4190	0.2033	0.2066	0.1651	0.1630
84	0.4267	0.4284	0.2033	0.2107	0.1657	0.1676
87	0.4321	0.4376	0.2033	0.2146	0.1666	0.1722
90	0.4507	0.4466	0.1690	0.2169	0.1756	0.1768

APPENDIX C

Comparison of Calculated and Experimental Moisture Sorption Rate Data Using Elovich and Zhabrova's Equation

Table C - 1. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Elovich and Zhabrova's Equation in Stack of Jute Bags at 12 % Initial Moisture Content and 26.7 ^{o}C (80 ^{o}F).

Days	Environmental Condition (R.H)					
	70 %		80 %		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	0.0159	0.0000	-0.0743	0.0000	0.1110
3	0.0190	0.0159	0.0304	0.0543	0.0682	0.2557
6	0.1023	0.1227	0.1213	0.1719	0.3182	0.3878
9	0.1818	0.2210	0.3373	0.2802	0.5492	0.5093
12	0.3258	0.3121	0.4131	0.3806	0.6288	0.6218
15	0.3902	0.3970	0.5229	0.4741	0.7576	0.7265
18	0.4356	0.4765	0.5723	0.5616	0.8978	0.8245
21	0.5076	0.5513	0.6821	0.6439	0.9848	0.9165
24	0.5340	0.8218	0.7182	0.7215	1.0720	1.0033
27	0.5806	0.6885	0.7958	0.7950	1.1516	1.0854
30	0.5947	0.7518	0.8185	0.8647	1.1857	1.1632
33	0.9166	0.8120	0.8185	0.9311	1.3069	1.2373
36	0.9772	0.8695	0.9435	0.9944	1.4319	1.3079
39	0.9848	0.9245	0.9890	1.0549	1.4735	1.3754
42	1.0075	0.9771	1.0725	1.1128	1.4925	1.4400
45	1.0908	1.0275	1.1595	1.1884	1.5342	1.5020
48	1.1439	1.0761	1.2240	1.2218	1.5948	1.5815
51	1.2197	1.1228	1.2505	1.2732	1.6516	1.6188
54	1.2538	1.1678	1.3566	1.3228	1.8516	1.6740
57	1.2575	1.2112	1.3794	1.3706	1.7235	1.7272
80	1.2765	1.2532	1.4021	1.4168	1.7425	1.7787
63	1.2726	1.2938	1.4778	1.4615	1.7842	1.8285
66	1.3030	1.3331	1.4817	1.5048	1.8524	1.8787
69	1.3219	1.3712	1.5574	1.5468	1.8865	1.9234
72	1.3447	1.4082	1.5574	1.5875	1.9774	1.9687
75	1.3825	1.4441	1.8370	1.6271	1.9812	2.0127
78	1.4734	1.4790	1.7128	1.6655	2.0190	2.0555
81	1.4924	1.5129	1.7545	1.7029	2.0721	2.0971
84	1.5757	1.5460	1.7810	1.7393	2.0911	2.1378
87	1.5757	1.5782	1.8075	1.7748	2.1099	2.1770
90	1.5984	1.6096	1.8114	1.8094	2.1971	2.2154

Table C - 2. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Elovich and Zhabrova's Equation in Stack of Polypropylene Bags at 12 % Initial Moisture Content and 26.7 °C.

Days	Environmental Condition (R.H)					
	70 %		80 %		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	-0.0398	0.0000	0.0185	0.0000	-0.0364
3	0.0076	0.0511	0.0038	0.0165	0.0380	0.0894
6	0.0303	0.1280	0.0796	0.1031	0.1175	0.2042
9	0.2196	0.1946	0.1591	0.1634	0.1743	0.3099
12	0.2690	0.2533	0.3031	0.2596	0.3409	0.4077
15	0.4281	0.3058	0.3676	0.3324	0.5682	0.4986
18	0.3676	0.3534	0.3713	0.4018	0.6289	0.5840
21	0.3676	0.3967	0.3789	0.4683	0.6476	0.6640
24	0.3145	0.4367	0.4092	0.5321	0.7500	0.7395
27	0.4565	0.4736	0.5039	0.5933	0.8409	0.8108
30	0.5039	0.5080	0.5380	0.6522	0.8976	0.8785
33	0.5759	0.5402	0.7312	0.7089	0.9659	0.9429
36	0.5635	0.5704	0.8714	0.7637	1.0494	1.0043
39	0.6024	0.5989	0.8638	0.8166	1.1062	1.0630
42	0.6762	0.6259	0.9509	0.8677	1.2046	1.1192
45	0.6972	0.6514	0.9547	0.9172	1.2312	1.1731
48	0.7009	0.6758	0.9964	0.9852	1.3182	1.2249
51	0.7047	0.6990	1.0570	1.0117	1.3410	1.2747
54	0.7350	0.7211	1.0911	1.0569	1.3713	1.3227
57	0.7464	0.7423	1.1859	1.1008	1.3940	1.3690
60	0.7891	0.7627	1.2047	1.1435	1.4357	1.4138
63	0.7426	0.7623	1.2123	1.1850	1.4546	1.4570
66	0.7501	0.8011	1.2237	1.2255	1.4887	1.4969
69	0.8222	0.8192	1.2351	1.2649	1.5190	1.5396
72	0.8373	0.8367	1.2386	1.3034	1.5342	1.5790
75	0.8524	0.8538	1.2892	1.3409	1.5968	1.6172
78	0.8636	0.8700	1.3184	1.3776	1.6213	1.6544
81	0.8790	0.8858	1.3752	1.4133	1.6630	1.6906
84	0.8904	0.9011	1.4320	1.4463	1.6554	1.7256
87	0.9245	0.9160	1.4669	1.4825	1.6971	1.7601
90	0.9206	0.9305	1.5192	1.5180	1.7273	1.7935

Table C - 3. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Elovich and Zhabrova's Equation in Stack of Jute Bags at 14 % Initial Moisture Content and 26.7 ^{o}C (80 ^{o}F).

Days	Environmental Condition (R.H)			
	80 %		90 %	
	ex.	cal.	ex.	cal.
0	0.0000	-0.0987	0.0000	-0.1100
3	0.0155	0.0358	0.0040	0.0610
6	0.0852	0.1428	0.1861	0.1887
9	0.2054	0.2321	0.2366	0.2907
12	0.2712	0.3086	0.2837	0.3756
15	0.2829	0.3754	0.3838	0.4483
18	0.3255	0.4349	0.4730	0.5119
21	0.4573	0.4883	0.5583	0.5884
24	0.5077	0.5369	0.6320	0.6193
27	0.8978	0.5815	0.7328	0.6855
30	0.7363	0.8226	0.7444	0.7079
33	0.7403	0.6608	0.8181	0.7470
36	0.7363	0.6964	0.8414	0.7833
39	0.7908	0.7298	0.8685	0.8172
42	0.7944	0.7613	0.8801	0.8490
45	0.8177	0.7910	0.8801	0.8789
48	0.8255	0.8191	0.9288	0.9071
51	0.8565	0.8458	0.9770	0.9339
54	0.8449	0.8712	0.9537	0.9593
57	0.8565	0.8955	0.9926	0.9835
60	0.8875	0.9188	1.0003	1.0066
63	0.9185	0.9410	1.0197	1.0287
66	0.9766	0.9624	1.0275	1.0499
69	0.9728	0.9830	1.0468	1.0702
72	0.9921	1.0028	1.0778	1.0898
75	1.0193	1.0218	1.0817	1.1086
78	1.0348	1.0403	1.1186	1.1287
81	1.0388	1.0581	1.1168	1.1443
84	1.0502	1.0753	1.1380	1.1612
87	1.0851	1.0920	1.1515	1.1776
90	1.1123	1.1082	1.2252	1.1935

Table C - 4. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Shelled Corn Using Elovich and Zhabrova's Equation in Stack of Polypropylene Bags at 14 % Initial Moisture Content and 26.7 °C.

Days	Environmental Condition (R.H)			
	80 %		90 %	
	ex.	cal.	ex.	cal.
0	0.0008	-0.1137	0.0000	-0.1092
3	0.0241	-0.0188	-0.0156	-0.0274
6	0.0706	0.0658	0.0504	0.0473
9	0.0782	0.1372	0.0891	0.1181
12	0.1247	0.2005	0.1434	0.1798
15	0.1908	0.2573	0.1821	0.2392
18	0.2294	0.3087	0.2210	0.2948
21	0.2914	0.3557	0.2791	0.3471
24	0.3534	0.3990	0.3373	0.3964
27	0.4231	0.4391	0.3760	0.4431
30	0.5123	0.4765	0.4788	0.4874
33	0.5278	0.5115	0.5815	0.5296
36	0.5859	0.5444	0.6086	0.5698
39	0.8053	0.5754	0.8706	0.6082
42	0.6478	0.6048	0.6939	0.6450
45	0.6750	0.6327	0.7327	0.8803
48	0.6789	0.6592	0.7482	0.7143
51	0.7021	0.6845	0.7831	0.7469
54	0.7332	0.7087	0.8102	0.7784
57	0.7448	0.7318	0.8218	0.8088
60	0.7525	0.7541	0.8606	0.8382
63	0.7951	0.7754	0.8683	0.8666
66	0.8184	0.7960	0.8839	0.8941
69	0.8262	0.8158	0.8955	0.9207
72	0.8494	0.8349	0.9226	0.9466
75	0.8300	0.8534	0.9808	0.9717
78	0.8494	0.8713	0.9886	0.9962
81	0.8727	0.8888	0.9982	1.0199
84	0.8959	0.9053	1.0273	1.0430
87	0.8959	0.9218	1.0487	1.0658
90	0.9192	0.9374	1.0738	1.0875

Table C - 5. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Rough Rice Using Elovich and Zhabrova's Equation in Stack of Jute Bags at 12 % Initial Moisture Content and 26.7 °C (80 °F).

Days	Environmental Condition (R.H)					
	70 %		80 %		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	-0.0003	0.0000	0.0004	0.0000	-0.0070
3	0.0908	0.0855	0.0588	0.0580	0.0644	0.0831
6	0.1475	0.1278	0.1250	0.1278	0.1515	0.1840
9	0.1968	0.1667	0.1932	0.1885	0.2878	0.2375
12	0.1929	0.2028	0.2273	0.2421	0.3874	0.3048
15	0.2459	0.2364	0.2386	0.2902	0.3940	0.3668
18	0.2913	0.2678	0.2500	0.3338	0.4053	0.4243
21	0.2951	0.2974	0.2614	0.3736	0.4432	0.4779
24	0.3405	0.3253	0.4318	0.4103	0.4886	0.5282
27	0.3821	0.3517	0.4432	0.4443	0.5190	0.5754
30	0.3784	0.3768	0.5000	0.4759	0.5833	0.8200
33	0.4011	0.4008	0.5227	0.5058	0.6856	0.6623
36	0.4085	0.4234	0.5568	0.5335	0.6969	0.7024
39	0.4199	0.4451	0.5882	0.5598	0.7273	0.7408
42	0.4539	0.4660	0.6932	0.5848	0.7690	0.7770
45	0.4842	0.4859	0.6705	0.6083	0.7803	0.8116
48	0.4880	0.5051	0.6818	0.6307	0.8712	0.8452
51	0.5107	0.5236	0.6818	0.6522	0.8940	0.8772
54	0.5410	0.5414	0.7159	0.6727	0.9015	0.9080
57	0.5713	0.5586	0.7386	0.6923	0.9318	0.9377
60	0.5826	0.5752	0.7386	0.7111	0.9697	0.9662
63	0.5637	0.5913	0.7386	0.7292	0.9810	0.9938
66	0.5940	0.6069	0.7500	0.7466	1.0417	1.0205
69	0.5864	0.6220	0.7500	0.7634	1.0985	1.0463
72	0.5940	0.6366	0.7500	0.7796	1.1174	1.0713
75	0.6242	0.6508	0.7841	0.7953	1.0985	1.0955
78	0.6848	0.6646	0.7841	0.8104	1.1213	1.1190
81	0.6999	0.6781	0.7955	0.8251	1.1401	1.1418
84	0.7302	0.6912	0.8068	0.8393	1.1515	1.1640
87	0.7377	0.7039	0.8068	0.8531	1.1667	1.1856
90	0.7415	0.7163	0.8068	0.8665	1.1856	1.2066

Table C - 6. Comparison of Calculated and Experimental Moisture Sorption Rate Data of Rough Rice Using Elovich and Zhabrova's Equation in Stack of Polypropylene Bags at 12 % Initial Moisture Content and 26.7 ^{o}C.

Days	Environmental Condition (R.H)					
	70 %		80 %		90 %	
	ex.	cal.	ex.	cal.	ex.	cal.
0	0.0000	-0.0398	0.0000	0.0185	0.0000	-0.0364
3	0.0078	0.0511	0.0038	0.0185	0.0380	0.0894
6	0.0303	0.1280	0.0796	0.1031	0.1175	0.2042
9	0.2198	0.1948	0.1591	0.1834	0.1743	0.3099
12	0.2690	0.2533	0.3031	0.2596	0.3409	0.4077
15	0.4281	0.3058	0.3678	0.3324	0.5682	0.4988
18	0.3676	0.3534	0.3713	0.4018	0.6289	0.5840
21	0.3676	0.3987	0.3789	0.4683	0.8478	0.6640
24	0.3145	0.4367	0.4092	0.5321	0.7500	0.7395
27	0.4585	0.4736	0.5039	0.5933	0.8409	0.8108
30	0.5039	0.5080	0.5380	0.6522	0.8978	0.8785
33	0.5759	0.5402	0.7312	0.7089	0.9659	0.9429
36	0.5835	0.5704	0.8714	0.7637	1.0494	1.0043
39	0.8024	0.5989	0.8638	0.8188	1.1062	1.0830
42	0.6782	0.6259	0.9509	0.8677	1.2046	1.1192
45	0.6972	0.6514	0.9547	0.9172	1.2312	1.1731
48	0.7009	0.6758	0.9964	0.9652	1.3182	1.2249
51	0.7047	0.6990	1.0570	1.0117	1.3410	1.2747
54	0.7350	0.7211	1.0911	1.0569	1.3713	1.3227
57	0.7464	0.7423	1.1859	1.1008	1.3940	1.3690
60	0.7691	0.7627	1.2047	1.1435	1.4357	1.4138
63	0.7426	0.7823	1.2123	1.1850	1.4546	1.4570
66	0.7501	0.8011	1.2237	1.2255	1.4887	1.4989
69	0.8222	0.8192	1.2351	1.2649	1.5190	1.5396
72	0.8373	0.8367	1.2388	1.3034	1.5342	1.5790
75	0.8524	0.8538	1.2692	1.3409	1.5988	1.8172
78	0.8838	0.8700	1.3184	1.3778	1.6213	1.6544
81	0.8790	0.8858	1.3752	1.4133	1.8830	1.8908
84	0.8904	0.9011	1.4320	1.4483	1.6554	1.7258
87	0.9245	0.9160	1.4889	1.4825	1.6971	1.7601
90	0.9208	0.9305	1.5192	1.5160	1.7273	1.7935

APPENDIX D

Fortan Program Used to Solve for Parameters in Chung's Equation

```
c  This program is used to determine the parameters in the
c  Chung equation.
c
c
c                Written by : Purboyo Guritno
c
c            Agricultural Engineering Department
c
c                 KANSAS STATE UNIVERSITY
c
c
c**************** main program ***********************
c
      dimension rd(31,8),rm(31),r(31),db(2),b(2),z(31,2),dk(31),dd(31),
     &zt(2,31),ainv(2,2),d(2,31),y(31)
      do 95 i=1,31
         read(5,*)(rd(i,j),j=1,8)
   95 continue
      do 96 i=1,31
         r(i)=rd(i,7)
   96 continue
      ss=0.0
      icount=0
      iflag=0
      ssk=1000000.0
      icount=icount+1
c
c Initialize parameters k and D
c
      b(1)=0.0012460
      b(2)=0.0014817
   35 sst=ss
      call model(rm,b,t)
      call mult2(d,z,zt,ainv,dk,dd,b,t)
      do 100 i=1,31
         y(i)=r(i)-rm(i)
  100 continue
      do 205 i=1,2
            db(i)=0.0
            do 400 k=1,31
               db(i)=db(i)+d(i,k)*y(k)
  400       continue
  205 continue
      ss=0.0
      do 40 i=1,31
         ss=ss+(y(i))*(y(i))
   40 continue
      if (ss .gt. sst)then
         cor = 0.5
      else
         cor = 2.0
```

```
      endif
c
      do 70 i=1,2
         tmp=b(i) + cor*db(i)
         if((tmp) .le. 0.0)tmp=b(i)
         b(i)=tmp
   70 continue
c
      if (icount .lt. 10)then
            icount=0.0
            iflag=iflag+1
                  write(6,10) (b(i),i=1,2)
                  write(6,*)'ss= ',ss,'sst= ',sst,'iflag= ',iflag
            write(6,*)
      endif
      if (ss. lt. ssk) then
         write(6,*)
            write(6,10) (b(i),i=1,2)
            itmp=iflag*10+icount
            write(6,*)'ss= ',ss,'itmp =',itmp
            ssk=ss
      endif
      if((abs(1-sst/ss)) .gt. 0.00000001) go to 35
      write(6,*)
   10 format(5f15.8)
c
c Print out the parameters k and D
c
      do 46 i=1,2
         write(6,2000)b(i)
   46 continue
 2000 format(2f15.8)
      stop
      end
c
c****************** subprogram *********************
c
c
c****** matrix derivation
c
      subroutine deriv(dk,dd,b,t)
      dimension dk(31),dd(31),b(2)
      t=0.0
      p=3.14159265
      do 100 i=1,31
         sum=0.0
         do 200 n=1,1000
            sum=sum+(1.0/n**2)*(exp(-n**2*b(2)*t))
  200    continue
         dk(i)=(6.0/p**2)*exp(-b(1)*t)*sum*t
         t=t+3.0
```

```
  100 continue
      t=0.0
      do 300 i=1,31
         sum=0.0
         do 400 n=1,1000
            sum=sum+exp(-n**2*b(2)*t)
  400    continue
         dd(i)=(6.0/p**2)*exp(-b(1)*t)*sum*t
         t=t+3.0
  300 continue
      return
      end
c
c***** set up matrix z containing derivation of the parameters
c
      subroutine matz(z,dk,dd,b,t)
      dimension z(31,2),dk(31),dd(31),b(2)
      call deriv (dk,dd,b,t)
      do 100 i=1,31
         ni=1
         z(i,ni)=dk(i)
         z(i,ni+1)=dd(i)
  100 continue
      return
      end
c
c***** transpose of matrix z
c
      subroutine matzt(zt,z,dk,dd,b,t)
      dimension zt(2,31),z(31,2),dk(31),dd(31),b(2)
      call matz(z,dk,dd,b,t)
      do 100 i=1,31
      do 100 j=1,2
         zt(j,i)=z(i,j)
  100 continue
      return
      end
c
c***** multiply matrix z transpose and matrix z
c
      subroutine mult1(c,z,zt,dk,dd,b,t)
      dimension c(2,2),z(31,2),zt(2,31),dk(31),dd(31),b(2)
      call matz(z,dk,dd,b,t)
      call matzt(zt,z,dk,dd,b,t)
      do 100 i=1,2
         do 200 j=1,2
            c(i,j)=0.0
            do 300 k=1,31
               c(i,j)=c(i,j)+zt(i,k)*z(k,j)
  300       continue
  200    continue
```

```
  100 continue
      return
      end
c
c***** inversion of matrix (zt x z)
c
      subroutine ainver(ainv,z,zt,dk,dd,b)
      dimension ainv(2,2),c(2,2),z(31,2),zt(2,31),dk(31),dd(31),
     &b(2),a(2,4)
      call mult1(c,z,zt,dk,dd,b,t)
      do 20 i=1,2
         do 10 j=1,2
            a(i,j)=c(i,j)
            a(i,j+2)=0.0
   10    continue
         a(i,i+2)=1.0
   20 continue
      do 200 j=1,2
         if (a(j,j) .eq. 0.0)then
            iflag=0
            do 299 i=1,2
               if (a(i,j) .ne. 0.0) iflag=1
  299       continue
            if (iflag .eq. 0) go to 200
            do 300 i=j,2
               if(a(i,j) .ne. 0.0) ii=i
  300       continue
            do 310 k=j,4
               tmp=a(ii,k)
               a(ii,k)=a(j,k)
               a(j,k)=tmp
  310       continue
            s=1.0/a(j,j)
         else
            s=1.0/a(j,j)
         endif
         do 201 k=j,4
            a(j,k)=a(j,k)*s
  201    continue
         do 202 i=1,2
            if(i-j) 203,202,203
  203       aij=-a(i,j)
            do 204 k=j,4
               a(i,k)=a(i,k)+aij*a(j,k)
  204       continue
  202    continue
  200 continue
      do 40 i=1,2
         do 30 j=1,2
            ainv(i,j)=a(i,j+2)
   30    continue
```

```
   40 continue
      return
      end
c
c***** multiply matrix a inverse (ainv) and z transpose
c
      subroutine mult2(d,z,zt,ainv,dk,dd,b,t)
      dimension d(2,31),z(31,2),zt(2,31),ainv(2,2),dk(31),dd(31),b(2)
      call ainver(ainv,z,zt,dk,dd,b)
      call matzt(zt,z,dk,dd,b,t)
      do 100 i=1,2
         do 200 j=1,31
            d(i,j)=0.0
            do 300 k=1,2
               d(i,j)=d(i,j)+ainv(i,k)*zt(k,j)
  300       continue
  200    continue
  100 continue
      return
      end
c
c***** model
c
      subroutine model(rm,b,t)
      dimension rm(31),b(20)
      t=0.0
      p=3.14159265
      do 100 i=1,31
         sum=0.0
         do 200 n=1,1000
            sum=sum+(1.0/n**2)*(exp(-n**2*b(2)*t))
  200    continue
         rm(i)=1-(6.0/p**2)*exp(-b(1)*t)*sum
         t=t+3.0
  100 continue
      return
      end
```

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MOISTURE SORPTION OF BAGGED GRAIN STORED UNDER TROPICAL CONDITIONS

by

PURBOYO GURITNO

B.S., Bogor Agricultural University, Indonesia, 1982

AN ABSTRACT OF A MASTER'S THESIS

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Department of Agricultural Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

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It is more difficult to maintain quality of bagged grain in humid tropics than in any other region. Due to the high relative humidity of the environment, moisture of the dried grain increases during storage. The increase in moisture causes various pest invasion and consequent quality deterioration. However, only a few studies have been conducted to explain the moisture transfer phenomenon in bagged grain.

The objectives of this study were, first, to determine the rate of moisture sorption of grain in bags, second, to explain the moisture sorption by the use of the accepted moisture sorption models, and, third, to assess the difference in moisture sorption rate due to the fiber from which the bag is woven (e.g. jute bag vs polypropylene bag).

Experiments were conducted within a 9.21 x 4.50 x 2.59 m environmental chamber using shelled corn and rough rice. Three relative humidities, 70 %, 80%, and 90 %, two initial moisture content (w.b), 12 % and 14 %, and two types of bag materials (jute and polypropylene bags) were studied in the experiment for shelled corn. For rough rice only one level of moisture (12 % w.b) was studied and all other variables were same as for shelled corn. The temperature was kept constant at 26.7 ^{o}C (80 ^{o}F) for all the experiments. The study was conducted for a 0.91 x 0.91 x 0.91 m stack size. The moisture contents of the samples taken from 3 different places in the stack, namely 0 cm (stack surface), 46 cm from the surface (center), and 22.88 cm from the surface (in between), were determined every 3 days. The change of the moisture content with respect to time was observed to determine the effects of initial moisture content, relative humidity, and bag materials on moisture sorption rate. Chung's, Wicke's, Patrick and Payne's, and Elovich and Zhabrova's equations were used to fit the experimental data.

It was found that the moisture sorption rate of water vapor by shelled corn and rough rice increased with decreasing initial moisture content or increased with increasing relative humidity. After 90 days in the storage, the moisture at the surface of the stack of shelled corn at initial moisture of 14 % w.b contained in jute and polypropylene bags, and subjected to 90 % relative humidity and 26.7 ^{o}C (80 ^{o}F) air, increased to 15.79 % and 15.46 %, respectively. At this level of moisture grains become very prone to insect and fungal attack. The rough rice in this environmental condition did not increase to such a high moisture level. The grain did not have enough time to reach the equilibrium moisture with the coresponding environmental air. Grain in jute bags adsorbed and desorbed moisture more readily than grain in polypropylene bags. The experimental data obtained in this study correlated well with Chung's and Elovich and

Zhabrova's adsorption rate equations.