AN INVESTIGATION OF DRYING AND SORPTION CHARACTERISTICS OF GRAIN SORGHUM

BY

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

Date 25/12/1996 ....

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This thesis has been submitted with our approval as University supervisors.

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ABSTRACT

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Published data on sorption and drying characteristics of sorghum grains is inadequate and scattered over temperature and relative humidity ranges. There is need to generate more data, test it on the existing models, and to develop new models that can fit a wide range of temperature and relative humidity.

Sorption data for adsorption and desorption of water by sorghum grains were obtained at 25°C, 40°C, 55°C and 70°C over a relative humidity range of 0.11-0.97, using a static gravimetric method. The experimentally obtained data for three sorghum varieties (White, Brown and Red) were used to evaluate the suitability of BET, Halsey, Henderson, Oswin, Smith and GAB sorption models. The models' parameters were computed using an iterative non-linear computer program. The experimental data was also fitted to an empirical model using multiple regression analysis and the results were compared to those from the above models. Monolayer moisture contents for the three varieties were determined from BET and GAB models.

The equilibrium moisture content (EMC) of grain sorghum was found to be independent of variety but was dependent on temperature. Both desorption and adsorption isotherms were sigmoid in shape (BET type II) and exhibited hysteresis phenomenon. Comparison between the empirical model and the other models indicated that no model was significantly superior to the empirical model. The GAB model fitted the sorption data over the entire relative humidity range better than all tested models. The ranking based on order of best fit was as follows: 1.GAB; 2.Henderson; 3.Empirical; 4.Oswin; 5.Smith; 6.Halsey; 7.BET.

Drying characteristics of both naturally moist and rewetted grain sorghum were also studied. Drying air temperature ranged between 40°C and 100°C. Two air flow rates were used. Thin layer drying equations based on Pabis and Henderson equation and Page model were developed. Drying air temperature was the major factor affecting drying rates of sorghum grains. The difference in sorghum varieties also influenced the drying rates. These differences were more pronounced at high air flow rates. The relationship between parameter k in Pabis and Henderson equation and drying air temperature was found to be of Arrhenius type. Parameter K in Page equation, for naturally moist grains, was expressed as an exponential function of temperature terms. But for rewetted grains, it was an exponential function of temperature terms, air flow rate,

relative humidity and initial moisture content. Parameter N in Page equation was expressed as an exponential function of temperature. Page equation fitted drying data better than Pabis and Henderson equation.

To my wife Grace and daughter Joy

from whom the time devoted to this thesis

was withdrawn

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NOMENCLATURE

θ	temperature, °C
$\underline{A}$	surface Area, m^2
A	constant, dimensionless
A_0, A_1	constants, dimensionless
Ads.	adsorption
ANOVA	analysis of variance
b_0, b	constants, dimensionless
B	constant, dimensionless
BROWN-R	Brown Rewetted
$\underline{C}$	sorption constant, dimensionless
C •	shape factor, dimensionless
C_1	constant, m^2s^{-1}
C_2	constant, per Kelvin
db	dry basis
Des.	desorption
D_1, D	diffusion coefficients, m^2s^{-1}
E	mean relative percentage deviation
EMC	equilibrium moisture content, (%db)
ERH	equilibrium relative humidity, (%)
exp	exponential
g	mass, grams
i	index
k, K	drying constants, per hour
$\underline{K}$	correction factor, dimensionless
k_0, k_1	constants, per hour

K_0, K_1, K_2....K_{12}	constant, dimensionless
m	length, metre
M	moisture content, decimal(db)
M_e	equilibrium moisture content, decimal(db)
M_m	monolayer moisture content, decimal(db)
M_o	moisture content at t=0, decimal (db)
MR	moisture ratio, dimensionless
n	index
N	Page drying constant, dimensionless
N_0, N_1, N_2....N_{12}	constants, dimensionless
r, R	radius of particles, metre
R^2.	coefficient of regression
RED-R	Red Rewetted
RH	relative humidity, decimal
s	time, second
β_1	constant, dimensionless
β_2	constant, per Kelvin
t	time, hours
T	absolute temperature, Kelvin
v	variance of regression
V	volume, m3
V	air flow rate , ms^{-1}
WHITE-R	White Rewetted
X	dimensionless time

1. INTRODUCTION

Sorghum <u>(SORGHUM VULGARE)</u> is a drought resistant crop requiring 300-380mm of rainfall during the growing season. It can regularly out-yield maize in many of the drier parts of East Africa. Sorghum is a traditional staple crop in the region and the vast genetic variability found in the area is not paralleled by any other region. All the major sorghum ecological zones found world wide are present in East Africa (Gebrekidan, 1982). Sorghum production is on the increase due to introduction of new varieties, the use of fertilizers and weed and pests control measures. In Kenya sorghum ranks third (below maize and wheat) in order of importance among cereals both by production and consumption (Ruto, 1982; F.A.O, 1992).

Due to frequent drought in the Sahel region, the Horn of Africa and East Africa, the agricultural policies of these areas are emphasizing on growing of drought resistant crops such as sorghum.

Sorghum is very vulnerable to pests, hence its potential as a drought resistant crop has not been fully utilised. Early harvesting (at physiological maturity) followed by drying would be a viable solution. Drying and sorption characteristics of grain sorghum are a prerequisite in the design of drying and storage systems. These characteristics are well summarised in form of drying and sorption models. These are mathematical equations that can predict the drying rate and equilibrium moisture content respectively.

Thin layer drying equations and sorption isotherms are available for maize, wheat and barley, but little data on these properties have been published for small grains (Brooker et al., 1992). Current literature reveals that this information is inadequate and scattered over temperature and relative humidity ranges (Day and Nelson 1965; Ngoddy and Bakker Arkema, 1970; Iglesias and Chirife, 1982; Pappas and Rao, 1987; Saravacos et al., 1986; Sun and Woods, 1993; Paulsen and Thompson, 1973; Misra and Brooker, 1980; Waananen et al., 1993). This is particularly so for data on grain Sorghum.

There is need to generate more data to fill the information gaps that exist, to develop new models and to test and evaluate the applicability of existing models to different types of food. Finally the need to develop models to fit a wide range of temperature and relative humidity still exists. It was against this background that a study was undertaken with general objectives of investigating and modelling the drying and equilibrium moisture characteristics of grain sorghum. The specific objectives of this study were as follows:

1. To develop thin layer drying models for sorghum grains
2. To test the suitability of six pre-selected models in predicting the equilibrium moisture content (EMC) of grain sorghum.
3. To test the effects of temperature and three sorghum varieties on model parameters.
4. To develop a generalized EMC model for sorghum grains.

The above specific objectives were based on the following hypotheses.

1. Thin layer drying characteristics of grain sorghum can be predicted adequately by drying models incorporating air temperature, initial moisture content and equilibrium moisture content (EMC).
2. Existing models can predict equilibrium moisture of grain-sorghum over some relative humidity ranges
3. Empirical model can fit EMC data for grain sorghum over a wider range of relative humidity than the existing theoretical models.

2. LITERATURE REVIEW AND THEORETICAL ANALYSIS

2.1 Equilibrium Moisture Content

Equilibrium Moisture Content (EMC) is a fundamental characteristic of biological materials that influences virtually every aspect of handling, drying, storage, manufacturing and consumption of food products (Ngoddy and Bakker Arkema, 1970; Iglesias and Chirife, 1982; Rockland and Stewart, 1981; Lagoudaki and Demertzis, 1993). EMC is defined as the moisture content of a material after it has been exposed to a particular environment for an infinitely long period of time. The EMC is dependent upon the humidity and temperature conditions of the environment. The influence of pretreatment, chemical composition and species differences in regard to sorption isotherms has of late attracted much interest from researchers. EMC of any product is a result of integrated hygroscopic properties of its individual components. Consequently, any change in chemical composition will affect the EMC. Komeyasu and Iyama (1974) reported that EMC of spray dried citrus Juice was affected by its pulp content. The degree of proteolysis affects the sorption behaviour of gruyere cheese (Malthlouthi et al., 1981). Bolin (1980) observed that sugar content of fresh raisins influenced EMC. The higher the fat content the lower the EMC at any specific relative humidity (Van Twisk, 1969, Heldman et al., 1965). Lagoudaki and Demertzis (1993) noted that the chemical composition of various foods affects the hysteresis effects. The particle size distribution does not influence the EMC. Gur - Ariah et al. (1967) working on wheat flour found the EMC to be independent of particle size distribution. The pore size of dried food has no effect on EMC (King et al., 1968). Saravacos (1967) reported that heat pretreatment had significant effect on EMC of apples and potatoes. Similar results have been reported by Hayakawa et al. (1978) working on coffee products and by Bolin (1980) who found the EMC of sun-dried raisins to be lower than that of Vacuum - dried grapes at the same relative humidity. Some researchers have studied the effect of variety on EMC. Putranon et al. (1979) found this effect on different paddy rice cultivars to be insiginificant. Pixton and Warbutton (1977) compared adsorption and desorption of three varieties of rapeseed. Sokhansanj et al. (1986) concluded that there was no difference between EMC for different varieties of rapeseed.

To obtain water sorption isotherms, EMC values must be determined and then plotted against the relative humidity at constant temperature. Procedures for obtaining water sorption isotherm for foods have been described in detail by Gal (1975), Labuza et al. (1976), Troller and Christian (1978) and Gal (1978). Brooker et al. (1992) and Iglesias and Chirife (1982) have given the methods in a summary form.

The most popular method is the gravimetric method (Sun and Woods, 1993). In this method static systems or dynamic systems can be used. In static method the grain is allowed to come to equilibrium in still, moist air while in dynamic method the air is mechanically moved.Dynamic method is faster that the static method which takes approximately two weeks. In both cases temperature and relative humidity are controlled by use of thermostat and acid or salt solutions respectively. Various concentrations of the same acid will permit studies over the entire range of relative humidity. Acids have not been used extensively because of the danger in handling them and because there may be small change in relative humidity of air during the course of the experiment due to an increase or decrease in concentration of the acid solution (Brooker et al., 1992). Saturated Salt Solutions are safer to use and maintaining saturation is easy because as water evaporates, salt precipitates and therefore relative humidity remains constant. A more rapid and accurate method of determining EMC of grains is by measuring directly the vapour pressure exerted by moisture in the Kernels in a previously evacuated jar. In this case an accurate manometer, closed glass tube system and vacuum pump are required thereby making the process very expensive (Iglesias and Chirife, 1982; Brooker et al., 1992; Chen and Morey, 1989; Madamba et al., 1993).

Available literature reveals very little sorption data on sorghum grains. Fenton (1941) reported adsorption isotherms for Blockhull Kajr sorghum variety at 4.4°C, 21.1°C, and 32.2°C. Ayerst (1965) used dew point method to determine both adsorption and desorption isotherms of two sorghum varieties known as Bukura Mahemba and Wiru at 25°C and 35°C while Dunstan et al. (1972) reported some work on adsorption and desorption characteristics of grain sorghum.

2.2 EMC Models

A number of theoretical, semi-theoretical and empirical models have been proposed for computing the moisture equilibrium for cereal grains. Most of the existing theoretical and semi theoretical models are based on three basic concepts (Ngoddy and Bakker Arkema, 1970):

1. Polanyi adsorption potential theory
2. The kinetic concept as exemplified by BET theory of multimolecular adsorption and its numerous modifications.
3. Zsigmondyy's capillary condensation theory.

Others are purely empirical. The following requirements have been suggested for EMC models: the experimental curve must be described mathematically for practical applications like drying; the equation should have a simple form and the least possible number of parameters to describe the data adequately; the parameters should be physically significant; temperature dependence of the parameters should be included in its analysis; and the effect of hysteresis should be considered (Madamba et al., 1993).

These models are of practical importance in many aspects of food preservation by dehydration such as prediction of drying times and shelf life of dried products in packaging materials (Labuza et al., 1976; Logoudaki and Demertzis, 1993). They also provide information directly useful in simulation and optimal design of driers and the prediction of equilibrium conditions of the mixed products with different moisture contents. Besides these practical interests, the isotherm equation is also needed for evaluating the thermodynamic functions of the water adsorbed in foods (Boquet et al., 1978).

Several attempts have been made to develop predicting models for the desorption and adsorption of vapours by biological and polymeric materials. However, there does not exist in the available literature any general satisfactory model for water sorption by biological materials. The primary reason for this inadequacy is that each of the existing sorption models has emanated from either one of the above mentioned three fundamental concepts,none of which is self sufficient as an exclusive theory of sorption (Ngoddy and Bakker Arkema, 1970; Brooker et al., 1992; Chirife and Iglesias, 1978).

Labuza (1968) reviewed some of the existing adsorption and desorption equations for food systems. In particular, he analyzed the theoretical basis of the isotherms following three principles; kinetic, potential and capillary condensation approach. Chirife and Iglesias (1978) discussed the validity of 23 equations that had been proposed to describe adsorption and desorption phenomena of food materials. Boquet et al. (1978) evaluated eight, two-parameter equations for 39 food isotherms obtained from literature. Pappas and Rao (1987) working on cowpeas evaluated the suitability of six pre-selected sorption models at five different temperatures. These models were then compared with an empirical linear model based on multiple regression.

Zuritz et al. (1979) tested the validity of three sorption models on smooth hulled medium grain rice variety at 10°C,20°C,25°C,30°C and 40°C and relative humidity ranging from 11.2 to 92.5%. Young (1976) worked on Virginia type peanut and tested the suitability of five sorption models. Lagoudaki and Demertzis (1993) studied the adsorption and desorption of five food products. They then used seven equations to fit the sorption data. Iglesias and Chirife (1982) entirely devoted a handbook to water sorption data for food and food components. The volume contains more than 1000 isotherms with the mathematical descriptions of over 800 isotherms using nine popular models.

Sun and Woods (1993) reviewed literature on relationship between moisture content and equilibrium relative humidity. They also reviewed and discussed methods of EMC determination, types of isotherms and the sorption models used to fit the data. Madamba et al. (1993) studied the behaviour of garlic slices. They also tested the fitting ability of four sorption models for temperatures ranging from 20°C to 70°C and relative humidity values of 0.11 to 0.85. Chen and Morey (1989a) evaluated the fitting ability of four models to 18 grains and seed crops. Other similar studies on fitting ability of sorption models on sorption data has been reported by Mazza and Jayas (1991), Cervantes et al. (1993), Maroulis et al. (1988), Tsami et al. (1990), Mok and Hattiarachchy (1990), Sokhansanj et al. (1986) and Shuchmann et al. (1990). Akritidis et al. (1988) studied fitting ability of four models on sorption data for pumpkin seeds, kernels and hulls at temperature range of 10°C to 60°C and relative humidity values lying between 5 and 85%.

In this study six popular sorption models were selected. Temperature and relative humidity were treated as the independent variables. Below, a brief explanation is included to justify models selection.

2.2.1 The BET Model

The BET equation was first postulated by Brunauer et al.

(1938). This equation can be derived from kinetic and statistical mechanics and also from thermodynamic considerations (Pappas and Rao , 1987; Van den Berg and Bruin, 1978). The BET equation can be expressed as :

$$M = \frac{M_m C\ RH}{[1-RH][1+(C-1)RH]} \quad \ldots\ldots \quad 2.1$$

Where M is water uptake (kg/kg), M_m is monolayer moisture content (kg/kg), C is the sorption constant that depends on temperature. It is one of the oldest and popular isotherms for food. BET parameters have physical significance, especially the monolayer value which shows the level of moisture content at which dehydrated foods have optimum storage stability. This stability is a result of protective effects of water against oxygen adsorption and interaction of adjacent polar groups. The BET model is known to hold for relative humidity values up to about 0.5 (Labuza, 1968; Chirife and Iglesias, 1978; Pappas and Rao, 1987; Van den Berg and Bruin, 1978; Lagoudaki and Demertzis, 1993).

2.2.2 The Halsey Equation

The Halsey equation was developed in 1945 by Halsey to overcome the limitations of the BET theory (Halsey, 1948; Pappas and Rao, 1987; Lagoudaki and Demertzis, 1993). Halsey (1948) showed that the equation characterizes the type of interaction between vapour and the solid and is a good representation of adsorption data that conform to BET Type I, II and III isotherms. Iglesias and Chirife (1982) have shown that Halsey equation has been used successfully by many researchers to fit the sorption data of different foods. Halsey equation is expressed as (Pappas and Rao, 1987):

$$M = \left[\frac{-A}{T \ln(RH)} \right]^{1/B} \quad \ldots\ldots\ldots \quad 2.2$$

Where A and B are constants that vary with temperature, T is temperature in Kelvin.

2.3.3 The Henderson Equation

The Henderson equation is an empirical equation and has been tested for a variety of products, including cereal grains and grain legumes. Young (1976) and Chirife and Iglesias (1978) found that the equation fitted experimental data for a variety of foods. Zuritz et al. (1979) used an empirically modified Henderson equation to describe desorption isotherms of rice from 10°C to 40°C. Other researchers who have used equations derived from Henderson equation and have found them to have good fitting ability include Sun and Woods (1993), Madamba et al. (1993), Chen and Morey (1989), Sokhansanj et al. (1986), Akritidis et al. (1988). Henderson equation can be written as (Pappas and Rao, 1987):

$$M = \left[\frac{-1}{A\,T} \ln(1-RH) \right]^{1/B} \quad \ldots\ldots\ldots \quad 2.3$$

Where A and B are constants that vary with temperature and T is temperature in Kelvin.

2.2.4 Oswin Equation

The Oswin equation was used initially to calculate the useful life of water sensitive commodities in water vapour resistant packages (Oswin, 1946). Boquet et al. (1978) applied this equation together with several others and found that Oswin equation was the best for describing the isotherms of proteinaceous and starchy foods and reasonably good for meat and vegetables (Pappas and Rao, 1987). Iglesias and Chirife (1982) and Lagadouki and Demertzis (1993) gave the following version:

$$M = A\left[\frac{RH}{(1-RH)}\right]^{B} \quad \ldots\ldots\ldots \quad 2.4$$

where A and B are temperature dependent constants.

2.2.5 The Smith Equation

The Smith equation was developed in order to describe water sorption by polymeric compounds with high molecular weights. This equation can be expressed as (Smith, 1947; Iglessias and Chirife , 1982; Pappas and Rao, 1987)

$$M = A - B\ln[1-RH] \quad \ldots\ldots\ldots \quad 2.5$$

where A and B are constants that vary with temperature. Becker and Sallans (1959) found that this equation could be used to describe reasonably well desorption isotherms of wheat between 0.5 and 0.95 relative humidity range. Young (1976) applied the same equation to sorption data of Virginia type peanuts. He showed that this equation can describe isotherms for relative humidity values higher than 0.3.

2.2.6 The GAB Model

The GAB model is the most widely accepted model for sorption isotherms in recent years. GAB model is an extension of the BET model. It is reported to give a remarkable fit over a wide range of relative humidity (up to 0.9) and a very good evaluation for the amount of water tightly bound by the primary adsorption sites (Lagoundaki and Demertzis, 1993; Madamba et al., 1993; Mazza and Jayas, 1991; Cerventes et al., 1993; Maroulis et al., 1988; Tsami et al., 1990; Mok and Hattiarachchy, 1990; Schuchmann et al., 1990). Current literature reveals the superiority of the GAB model and this explains why it has been adopted by the European Cooperation of Science and Technology Research (COST 90) Group on water activity. The GAB model is expressed as:

$$\frac{M}{M_m} = \frac{(C\ K\ RH)}{[1 - K\ RH][(1 - K\ RH + C\ K\ RH]} \quad \ldots\ldots\ 2.6$$

where $\underline{C}$ is Guggenheim s constant and $\underline{K}$ is correction factor, both of which vary with temperature, and M_m is monolayer moisture content.

2.3 Drying

Drying is a process of simultaneous heat and moisture transfer. The heat evaporates the moisture which is removed from the drying product by air. A number of biological products, when drying as single particles under constant external conditions, exhibit a constant rate moisture loss during the initial drying period, followed by a falling rate drying period. Cereal grain kernels, however, usually dry entirely within the falling rate drying period (Brooker et al., 1992).

To predict the moisture content at any time during drying process the drying rate must be expressed as a mathematical equation that depicts the behaviour of grains under particular conditions (Mwithiga, 1990). Developing of mathematical models to describe drying of agricultural products has been a topic of research in many fields for several decades. Bakker Arkema et al. (1974), Morey et al. (1978), Parry (1985), Brooker et al. (1992) and Jayas et al. (1991) have reviewed most of the drying models presented in literature.

Theoretical, semi- theoretical and empirical equations have been developed for many drying products in the falling rate period. Only semi-theoretical and empirical relationships have proved useful to the drier designer (Brooker et al., 1992; Mwithiga, 1990).

2.4 Theoretical Drying Equations

Theoretical equations involve the determination of the combined effects of moisture, temperature and total pressure gradients in the products while at the same time changes in properties of drying products are taken into consideration. Physical mechanisms proposed for describing the transfer of moisture in capillary porous products such as cereals grain include (Brooker et al., 1992):

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

Luikov (1966) developed models for describing moisture removal from porous products. The generalized form of this Newtonian diffusion equation is:

$$\frac{\partial M}{\partial t} = D_j \left[\frac{\partial^2 M}{\partial r^2} + \left(\frac{C}{r} \right) \frac{\partial M}{\partial r} \right] \quad \ldots\ldots \quad 2.7$$

where M=moisture content (db) at time t in hours, C is shape factor, r is the radius of particle and D_j are diffusion coefficients.

Equation 2.7 has the following initial and boundary conditions:

$$\frac{\partial M}{\partial r} = 0, r = 0, t \geq 0 \quad \ldots\ldots \quad 2.8$$

$$M = M_e, r = R, t > 0 \quad \ldots\ldots \quad 2.9$$

$$M = M_0, 0 < r < R, t > 0 \quad \ldots\ldots \quad 2.10$$

Crank (1975) has given complete analytical solution of this equation. For a spherical body with a constant D, Brooker et al. (1992) have given the following solution to Equation 2.7:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[\frac{-n^2 \pi^2 X^2}{9} \right] \quad \ldots \quad 2.11$$

MR and X are dimensionless moisture ratio and time respectively, expressed as:

$$MR = \frac{M - M_e}{M_0 - M_e} \quad \ldots\ldots\ldots \quad 2.12$$

$$X = \frac{A}{V} (D t)^{1/2} \quad \ldots\ldots\ldots \quad 2.13$$

where M_e is equilibrium moisture content and M_o is moisture content at t=0. A, represents the surface area and V, the volume of the body.

To relate the diffusion coefficient with the shape of the material, a drying parameter K is introduced (Steffe and Singh, 1982):

$$K = \frac{X^2}{t} = \left(\frac{A}{V} \right)^2 D \quad \ldots\ldots\ldots \quad 2.14$$

By solving Equation 2.7 in spherical co-ordinates, Equation 2.14 reduces to:

$$K = \frac{D\, n^2\, \pi^2}{R^2} \quad \ldots\ldots\ldots \quad 2.15$$

This analytical equation has been used by researchers treating their products as composite spheres. Among them are Steffe and Singh (1980), who considered rice as a composite sphere of three concentric shells namely the endosperm, bran and hull. Noomhorm and Verma (1986) and Sharma et al. (1982) considered rough rice as a two component material while Bakshi and Chinnan (1984) estimated moisture transport parameters in various food components by a similar method using a non linear optimization technique with a search programme.

2.5 Semi-Theoretical Equations

A simplification of the solution of Equation 2.11 has frequently been used to predict the drying of grain by employing only the first term of Equation 2.11 (Brooker, et al., 1992; Nindo, 1991):

$$MR = \frac{6}{\pi^2} \exp\left[\frac{-D\,\pi^2\, t}{r_o^2}\right] = \frac{6}{\pi^2} \exp[-K\, t] \quad . \quad 2.16$$

where r_o is the radius of the grain.

A relationship suggested by Lewis (1921) similar to Equation 2.16 and analogous to Newton's Law of cooling is often used for grain drying analysis (Brooker et al., 1992; Barre, 1988):

$$\frac{dM}{dt} = k\,[\,M - M_e\,] \quad . \; . \; . \; . \; . \; . \; . \quad 2.17$$

This equation is based on assumption that during drying of porous hygroscopic material in the falling rate period the rate of change in moisture content is proportional to the instantaneous difference between moisture content of the material and the expected moisture content of the material when it comes into equilibrium with entering air (Jayas et al., 1991). Integrating Equation 2.17 yields:

$$MR = \frac{M - M_e}{M_0 - M_e} = \exp[-k\,t] \quad \ldots\ldots \quad 2.18$$

Equations 2.16 and 2.18 are referred to as the thin layer drying equations and K and k as the drying constants. The units of K and k are per hour or per second (Ross and White, 1972; Brooker et al., 1982). White et al. (1980) used Equation 2.18 to describe the drying behaviour of fully exposed popcorn.

2.6 Diffusion Coefficients and Drying Constants

Diffusion coefficients are grain and drying equation specific. Besides, diffusion coefficients or drying constants are applicable only to specific temperature and moisture content ranges. The relationship between diffusion coefficient (and thus drying constants) and grain temperature is usually of Arrhenius type (Ross and White, 1972; Brooker et al., 1992; Henderson and Pabis, 1961; Chu and Hustrulid, 1968):

$$D = C_1 \exp\left[\frac{-C_2}{T}\right] \quad \ldots\ldots\ldots \quad 2.19$$

where C_1 and C_2 are constants depending on particular grain and T is temperature in Kelvin. D has the units of m^2/sec. Values of D, K and k have been published for corn (Pabis and Henderson, 1961) while k values exist for wheat and barley (O'Callaghan et al., 1971).

2.7 Empirical Drying Equations

Several purely empirical thin layer drying equations have been developed for cereal grains. Thompson (1967) developed Equation 2.20 for shelled corn in temperature range 60°C to 150°C.

$$t = A \ln MR + B [\ln MR]^2 \quad \cdots\cdots \quad 2.20$$

where

$$A = -1.86178 + 0.00488\theta \quad \cdots\cdots \quad 2.21$$

$$B = 427.3640 \exp[-0.03301\,\theta] \quad \cdots \quad 2.22$$

where t is time in hours and θ is temperature in °C. Paulsen and Thompson (1973) used the same Equation 2.20 to form thin layer models for grain sorghum where :

$$A = -25.87 + 0.001075 [1.8\theta + 32]^2 \quad \cdots \quad 2.23$$

for

$$26.5 \le \theta \le 71\ ^\circ C$$

$$A = 0.54 - 0.0017 [1.8\theta + 32] \quad \cdots \quad 2.24$$

for

$$71 < \theta \leq 115.5\,^{\circ}C$$

$$B = 30.35 \exp[-0.018\,(1.8\theta + 32)] \quad \cdots \quad 2.25$$

for

$$26.5 \leq \theta \leq 115.5\,^{\circ}C$$

Becker (1959) determined the drying rate data for wheat and proposed the following equations:

$$MR = 1 - 24.82\,[D\,t]^{1/2} + 142.29\,[D\,t] \quad \cdot \quad 2.26$$

for

$$[D\,t]^{1/2} < 0.034 \quad \cdots\cdots \quad 2.27$$

$$MR = 0.509 \exp[-629.68\,D\,t] \quad \cdots \quad 2.28$$

for

$$[D\,t]^{1/2} \geq 0.034 \quad \cdots\cdots \quad 2.29$$

To model thin layer drying of rough rice Noomhorm and Verma (1986) used Equation 2.11 with two terms in the series with the explanation that this grain could not be treated as a homogeneous material:

$$MR = A_0 \exp[-k_0 t] + A_1 \exp[-k_1 t] \quad . . \quad 2.30$$

Where A_0 and A_1 are constants.

Sharaf-Eldeen et al. (1980) successfully used a two term exponential model similar to Equation 2.30 to predict the drying behaviour of ear corn. Page (1949) and Sabbah (1968) modified Equation 2.18 to the following form:

$$MR = \exp[-k\, t^{N}] \quad . . . . \quad 2.31$$

where N is a decimal exponent.

Equation 2.31 has since then been used extensively to model the thin layer drying behaviour of cereals, oilseeds, earcorn and clover (Jayas et al., 1991). Misra and Brooker (1980) compiled data from literature on thin layer drying and rewetting of maize. They then used Equation 2.31 on the data to give thin layer drying and rewetting equations. They found k to be dependent on drying temperature and air velocity while N was dependent on relative humidity of air and initial moisture content. Working on soybeans, Overhults et al. (1973) modified Equation 2.31 to :

$$MR = \exp[-(k\, t)^{n}] \quad . . . . . . \quad 2.32$$

where

$$n = \beta_1 + \beta_2 T \quad . . . . \quad 2.33$$

$$\ln k = b_o + \frac{b}{T} \quad \ldots\ldots\ldots \quad 2.34$$

Where β1, β2, bo and b are constants.

They concluded that Equation 2.32 fitted the drying data better than Equation 2.31. White et al. (1980) employed Equations 2.32 to 2.34 on Soybeans and found a good agreement between predicted and observed values. Bakker Arkema (1984) noted the need to update the empirical drying rate equations for grains.

2.8. Factors Affecting Thin Layer Drying Rate

Drying air temperature (grain temperature), and initial grain moisture content are the major factors that control heat and moisture transfer rates. Others that have been given consideration in thin layer drying are air velocity, relative humidity and grain characteristics.

Air velocity has little effect on thin layer drying rate especially for flow rates less than 0.68m/s (Jayas et al., 1991; Misra and Brooker, 1980; Pabis and Henderson, 1962; Hutchinson and Otten, 1982; Syarief et al., 1984; Paulsen and Thompson, 1973). Relative humidity of the drying air has been reported to have significant effect on drying rates (Farmer et al., 1983; Misra and Brooker, 1980; Singh et al., 1983; Westerman et al., 1973). Grain type and characteristics have been found to affect drying rates. This can be explained theoretically by Equations 2.7 and 2.11 where physical properties of grain such as shape and radius are shown to affect drying rate. Work done by Kreyger (1972) and Stroshine et al. (1981) have confirmed this fact.

2.9 Rewetting of Grains

Under practical conditions rewetting of grains can occur in the fields, on transit, during deep bed drying or during storage. Very little work has been done on thin layer rewetting of grains (Misra and Brooker, 1980). Density and bulk porosity of rewetted grain changes with successive wetting and drying (Sokhasanj et al., 1984). Page equation has been used to describe drying characteristics of rewetted canola (Shatadal et al., 1989). The difference between adsorption and desorption is important when assessing the thin layer drying or rewetting equations. Much work is still needed to develop a better understanding of the nature of the sorption phenomenon, its significance in defining the storage potential of a product and its application to thin layer drying and rewetting of grain (Jayas et al., 1991).

2.10 Selection of Thin Layer Drying Models

Researchers have compared the many drying equations that appear in literature. Many researchers have found the 2 parameter Page equation (Equation 2.31) to be superior to other models. Misra and Brooker (1980) fitted Equation 2.31 to thin drying and rewetting data for corn from eight sources. Syarief et al. (1984) showed that among Equations 2.18, 2.20, 2.30 and 2.31, Equation 2.31 fitted data for sunflower seeds in the range of 27 to 90°C best. Bruce (1985) compared Equations 2.7, 2.18 and 2.31 using drying data for barley. He concluded that Equation 2.31 gave a much better overall drying curve. The two parameters of Page equation do not necessarily increase or decrease at the same rate, hence it is difficult to use it to compare different varieties using statistical methods (Jayas et al., 1991). The equation used most for comparison purposes is the one parameter Equation 2.18. On the basis of the above discussion the two Equations, 2.18 and 2.31 were selected to model the drying behaviour of grain sorghum.

3. MATERIALS AND METHODS

3.1 Sorghum Grains

Sorghum grains used in drying experiments were obtained directly from farms in Iuni area, Machakos district. This was because sorghum was in season in that area and it was easy to obtain wet grains. The grains used in sorption experiments were purchased from Gikomba market in Nairobi after they had been confirmed to have been bought in Machakos. This helped in reducing the sample variation mainly in terms of grain size and colour. The same grains were used in hydration experiments. The grains were classified using colour as either white, brown or red. The composition of the sorghum grains is given in appendix A. Grains with high moisture content (for drying experiments) were put in sealed polythene bags and preserved in a refrigerator. To rewet grains, samples were hydrated in desiccators over distilled water at room temperature.

3.2 EMC Determination

Sorghum grains were han picked to ensure they were free from all foreign materials. Before adsorption experiments were done, grain samples were dried in an oven at 40°C for two weeks and kept over phosphorous pentoxide (P_2O_5) for 15 days at room temperature (Saravacos et al., 1986, Tsami et al., 1990). For the measurement of desorption isotherm, grain samples were hydrated in desiccators over distilled water for two weeks at room temperature. This provided an environment of relative humidity equal to 100% (Lagoudaki and Demertzis, 1993, Saravacos et al., 1986, Tsami et al., 1990). Sorption isotherms were determined by static method through equilibration of moist (desorption) and dried (adsorption) samples over saturated salt solutions of known relative humidity at constant temperatures. Eleven saturated salt solutions corresponding to a relative humidity of 0.11 to 0.97 were used (see Table 3.1). The saturated salt solutions were transferred into plastic jars (hygrostats) such that they occupied a space of about 2cm at the bottom. The hygrostats were then placed at the right temperature for 24 hours to ensure that the solutions remained saturated. The hygrostats had provisions for placing grain samples in other small plastic containers. Duplicate samples of about 2g of each variety were put into the small plastic containers, ensuring that grains were fully exposed, and placed in the hygrostats which were then tightly closed. The hygrostats were then placed in constant temperature cabinets maintained at test temperatures ±0.5°C for equilibration to take place. Samples were then left for 15 days to equilibrate (Saravacos et al., 1986). Moisture content was then determined by placing sorghum grains in an oven at 130°C for 18 hours (Harl et al., 1959) and determining the loss in weight. Weight measurements were taken by analytical balance to an accuracy of 0.01g. To avoid spoilage due to mould, the same treatment as done by Gustafson and Hall (1974) and Zuritz et al. (1979) (that is application of a 2% weight mixture of 40% propionic acid and 60% acetic acid with 2% by weight sodium benzoate) was applied to grains at relative humidity of 90% and above. Preliminary tests showed no difference in EMC between treated and untreated grain samples. Similar results have been reported by Dunstan et al. (1972) working on sorghum grains

Table 3.1 Relative Humidity of Saturated Salt Solutions

SALT SOLUTION	TEMPERATURE °C				
	25	35	45	50	70
Potassium Sulphate	0.97	0.96	0.96	0.958	0.948
Potassium Chloride	0.96	0.86	0.85	0.85	0.80
Ammonium sulphate	0.79	0.79	0.79	0.79	-
Sodium chloride	0.75	0.75	0.75	0.75	0.75
Cupric chloride	0.67	0.67	0.67	-	-
Sodium Nitrate	-	-	-	0.687	0.657
Sodium Nitrite	0.6-45	0.625	0.62	0.6	-
Sodium Dichromate	-	-	-	0.544	-
Sodium Bromide	0.57	0.55	0.52	-	0.51
Magnesium Chloride	0.33	0.33	0.33	0.33	0.3
Lithium Chloride	0.112	0.112	-	-	0.11

Data for Licl adapted from (1) Githinji (1974)
(2) Brooker et al. (1992)

The rest is adapted from Pappas and Rao (1987)

3.3 Drying Experiments

A laboratory drier with six air flow rate settings and accurate temperature measuring and control system was used. Temperatures were kept to an accuracy of $\pm 0.5°C$. Prior to the start of experiments the drier was calibrated for air flow rate using a pitot tube and an inclined tube manometer. Single layers of about 2.5g of sorghum grains of each variety were placed in duplicate in shallow perforated trays. They were then placed in the drier pre-set at the test temperature and air flow rate. Samples were quickly withdrawn from the drier and weighed to find out the weight loss at various time intervals. Loss in weight-time data was collected until constant weight was achieved. All weight measurements were done using analytical balance to an accuracy of 0.01g. Since the drier had no instrument to measure relative humidity, a thermohydrograph was used to record relative humidity. The days on which drying experiments were done were carefully selected to minimize relative humidity fluctuations. These fluctuations were also minimised by ensuring that lights in the laboratory were kept on and all the doors and windows remained closed during the night. A sling psychrometer was used after every two hours to confirm the reading from the thermohydrograph. After the end of the two drying experiments, moisture content of the samples was determined by oven method (Harl et al., 1959).

4 RESULTS AND DISCUSSIONS

4.1 Sorption Isotherms

Tables 4.1 to 4.4 show the average equilibrium moisture contents for three sorghum varieties at different temperatures and equilibrium relative humidity. At all temperatures tested, higher relative humidity values gave higher EMC. The sorption isotherms for the three varieties are shown in Figures 4.1 to 4.8.

Table 4.1 EMC(%db) at 25°C

Variety and sorption Process	Relative Humidity, decimal								
	0.112	0.33	0.57	0.645	0.67	0.75	0.79	0.96	0.97
Red-Des.	5.70	9.83	12.84	15.34	16.08	16.67	18.75	20.33	24.60
Brown-Des.	5.23	9.58	12.53	14.66	15.98	17.60	19.85	21.05	23.97
White-Des.	5.77	9.57	12.80	14.41	15.12	18.18	19.03	20.98	24.26
Red-Ads.	8.72	9.52	12.15	14.20	14.46	16.14	17.70	19.99	24.87
Brown-Ads.	9.13	9.38	12.10	13.51	14.29	15.82	18.30	20.03	24.30
White-Ads.	9.08	9.24	12.72	13.04	14.89	16.14	18.44	19.29	24.26

Table 4.2: EMC (%db) at 40°C

Variety and Sorption Process	Relative Humidity, decimal								
	0.112	0.33	0.535	0.622	0.67	0.75	0.79	0.855	0.96
Red-Des.	5.16	9.28	11.11	14.32	15.34	15.77	17.35	18.13	23.47
Brown-Des.	5.05	8.58	12.14	14.04	14.52	15.57	17.77	17.81	23.66
White-Des.	5.28	8.96	11.58	14.29	14.35	15.27	16.90	17.09	24.03
Red-Ads.	4.92	9.14	10.01	10.40	13.20	15.16	17.14	18.04	23.04
Brown-Ads.	4.79	8.07	10.97	12.21	13.20	15.03	16.78	17.44	23.28
White-Ads.	5.57	8.16	11.10	11.22	13.50	15.20	16.50	17.04	22.95

Table 4.3 : EMC (%db) at 55°C

Variety/ Sorption Process	Relative Humidity, decimal								
	0.11	0.33	0.518	0.58	0.67	0.75	0.79	0.837	0.955
Red-Des.	3.95	6.80	10.39	10.96	15.27	15.71	16.77	16.83	23.34
Brown-Des.	4.38	7.01	10.63	10.87	14.65	15.22	16.04	16.83	23.56
White-Des.	5.08	7.39	9.88	10.91	13.14	15.05	16.60	16.72	23.33
Red-Ads.	3.52	5.15	8.95	10.56	12.34	14.14	14.67	16.31	21.30
Brown-Ads.	3.69	6.47	8.16	10.13	11.51	13.54	15.00	16.09	22.38
White-Ads.	2.58	6.12	8.64	10.34	11.22	13.91	14.76	15.52	21.81

Table 4.4 : EMC (%db) at 70°C

Variety/ Sorption Process	Relative Humidity, decimal								
	0.11	0.33	0.51	0.52	0.657	0.67	0.75	0.80	0.948
Red-Des.	3.05	5.31	7.56	8.59	9.67	11.70	12.50	12.80	22.50
Brown-Des.	3.16	5.26	7.89	8.40	9.44	9.92	12.34	12.90	22.45
White-Des.	2.77	5.69	7.80	8.54	9.65	10.05	12.19	12.99	22.35
Red-Ads.	1.92	3.47	7.03	7.89	9.43	9.50	12.26	12.64	21.00
Brown-Ads.	1.83	4.76	7.33	8.04	9.05	9.50	11.97	12.46	21.98
White-Ads.	2.00	4.40	7.23	7.47	9.04	9.57	11.80	12.73	21.40

The curves were found to be very similar. ANOVA based on randomised block design proved that there was no significant difference in EMC for the three varieties, at 5% level of significance. This is in agreement with many other researchers who have worked on different foods (Putranon et al., 1979; Pixton and Warburton, 1977; Sokhansanj et al., 1986). The EMC of sorghum grains is dependent on temperature. Specifically constant low relative humidity resulted in lower equilibrium moisture content at higher temperatures than at lower temperatures. At higher relative humidity (over 0.8), this trend was not always true. Similar results have been reported by Pappas and Rao (1987), Young (1976) and Zuritz et al. (1979) working on Cowpea, Virginia type peanuts and rice respectively. Average EMC values at each particular temperature, shown in Tables 4.5 to 4.8, were hence used for subsequent analysis.

Table 4.5: Average EMC (%db) at 25°C

Sorption Process	Relative Humidity, decimal								
	0.112	0.33	0.57	0.645	0.67	0.75	0.79	0.96	0.97
Desorption	5.57	9.66	12.72	14.80	15.73	17.48	19.21	20.79	24.28
Adsorption	8.99	9.38	12.32	13.58	14.55	16.03	18.15	19.77	24.48

Table 4.6 Average EMC (%db) at 40°C

Sorption Process	Relative Humidity, decimal								
	0.112	0.33	0.535	0.622	0.67	0.75	0.79	0.855	0.96
Desorption	5.16	8.94	11.61	14.22	14.74	15.54	17.34	17.68	23.72
Adsorption	5.09	8.46	10.69	11.28	13.30	15.13	16.81	17.51	23.09

Table 4.7: Average EMC (%db) at 55°C

Sorption Process	Relative Humidity, decimal								
	0.11	0.33	0.518	0.58	0.67	0.75	0.79	0.837	0.955
Desorption	4.47	7.07	10.30	10.91	14.35	15.33	16.47	16.79	23.41
Adsorption	3.26	5.91	8.58	10.34	11.69	13.86	14.81	15.97	21.83

Table 4.8: Average EMC (%db) at 70°C

Sorption Process	Relative humidity,decimal								
	0.11	0.33	0.51	0.52	0.657	0.67	0.75	0.80	0.948
Desorption	2.99	5.42	7.75	8.51	9.59	10.56	12.34	12.90	22.43
Adsorption	1.92	4.21	7.20	7.80	9.17	9.52	12.01	12.61	21.46

Figures 4.9, 4.10, 4.11 and 4.12 represent the sorption isotherms of grain sorghum derived from GAB model at 25°C, 40°C, 55°C and 70°C respectively. Adsorption values of EMC were generally lower than desorption values at any given temperature thereby exhibiting hysteresis phenomenon. Moisture sorption hysteresis is the existence of different paths for adsorption and desorption isotherms. Several theories and hypotheses have been advanced to explain sorption hysteresis (Sun and Woods, 1993). This phenomenon has theoretical and practical implications in foods. The theoretical implications range from general considerations of the irreversibility of the sorption process to the question of validity of the thermodynamic functions derived therefrom. The practical implications deal with the ease of drying, change in surface structure of the adsorbent by dehydration and the effects of hysteresis on chemical and microbiological

deterioration (Lagoudaki and Demertzis, 1993). Hysteresis may actually indicate non-equilibrium conditions at the end of sorption experiments, but almost every researcher has reported its existence between adsorption and desorption curves. Both desorption and adsorption isotherms were sigmoid in shape (BET type II). Each isotherm had three distinct parts: 1. mono-layer region (relative humidity less than 0.5; 2. multi-layer region (relative humidity between 0.5-0.8); 3. condensed water region (relative humidity over 0.8). This shape is typical for many biological materials, including cereal grains (Caurie, 1978; Brooker et al., 1982; Lagoudaki and Demertzis, 1993; Sun and Woods, 1993). It was evident that temperature affected the shape and the span of hysteresis effects. At 25°C the hysteresis effects were predominantly in multi-layer region and hardly was there any hysteresis in mono-layer and capillary condensation regions. The span steadily increased at 40°C and at higher temperatures hysteresis phenomenon was observed over the entire range of relative humidity tested. The hysteresis effects were maximum at multi-layer regions (relative humidity of about 0.67). The size of hysteresis effects decreased with increase in temperature. Similar findings were reported by Wolf et al. (1972) working on dehydrated foods. But, unlike in their work, the span increased with increase in temperature.

Different views have been raised on whether adsorption curve can cross over the desorption one (Pappas and Rao , 1987). In this study at 25°C and 40°C, the curves joined at very low and very high relative humidity but they did not cross over each other. ANOVA was carried out to test whether there was any difference in EMC between adsorption and desorption. The results showed that the differences were significant at all temperatures tested except at 25°C. This could be explained by the fact that the span of hysteresis was very short at 25°C. It was therefore necessary to calculate parameters for the two processes separately.

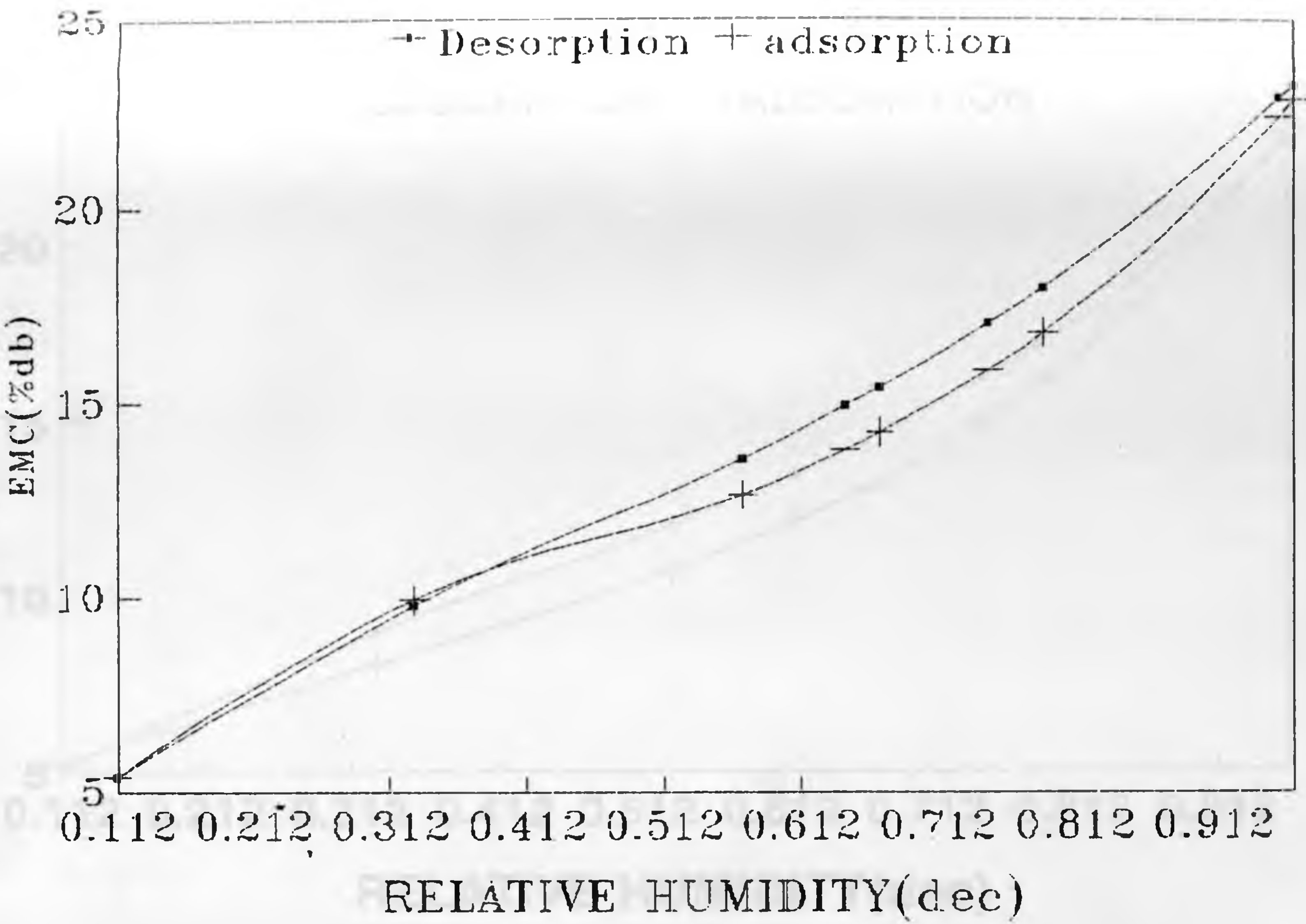


Figure 4.9 Sorption isotherms of grain sorghum (GAB model at 25°C)

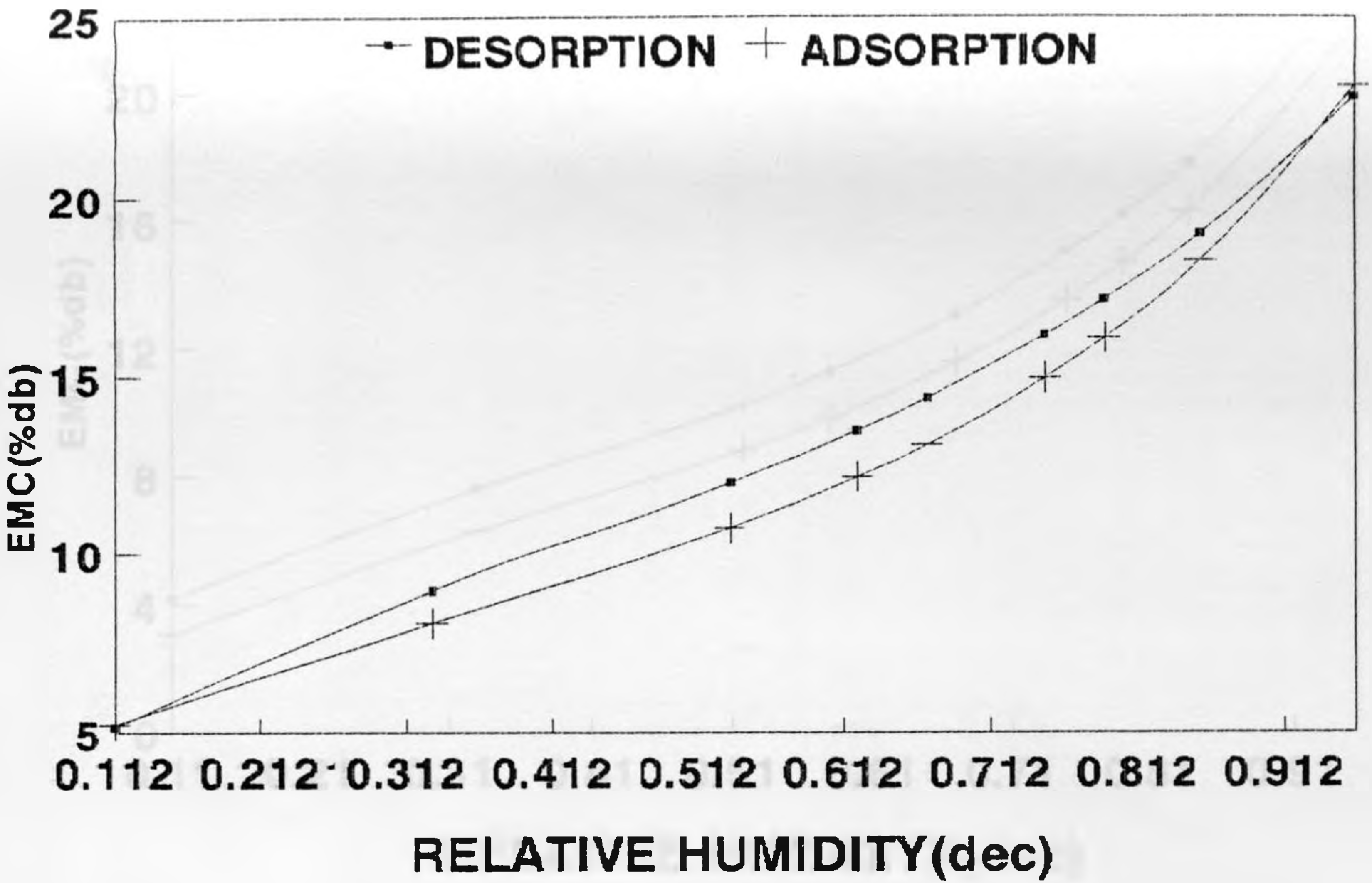


Figure 4.10 Sorption isotherms of grain sorghum (GAB model at 40°C)

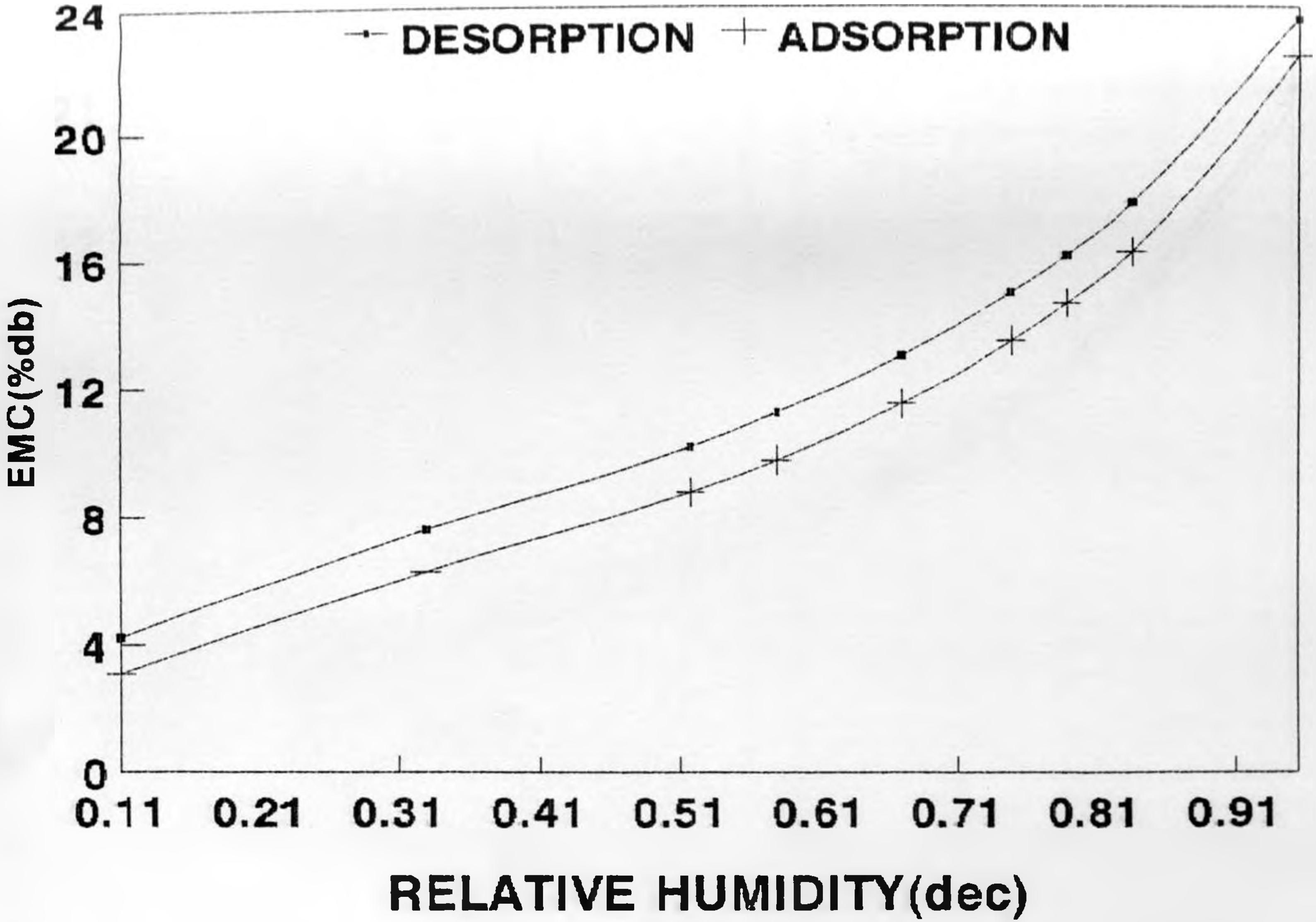


Figure 4.11 Sorption isotherms of grain sorghum (GAB model at 55°C)

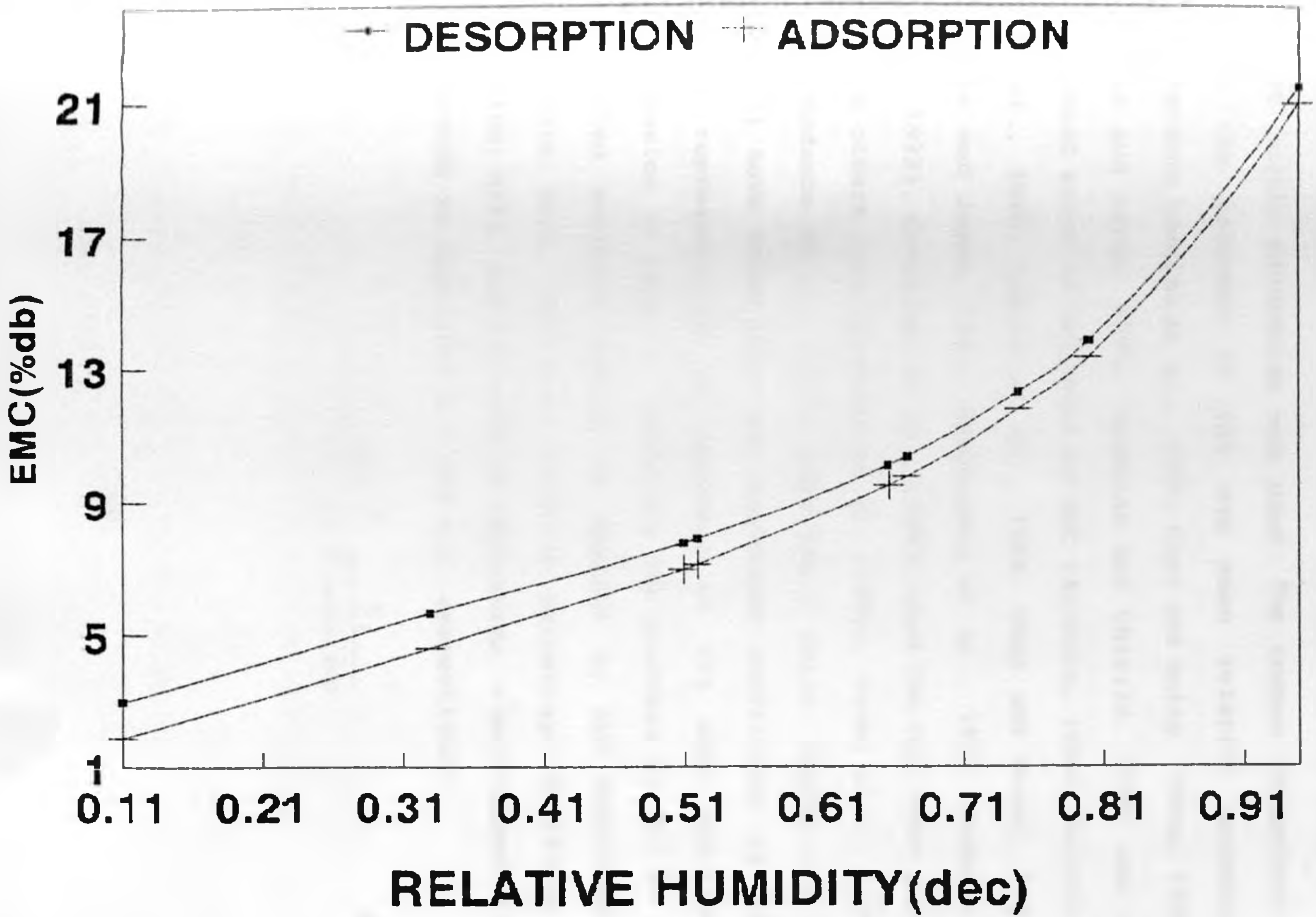


Figure 4.12 Sorption isotherms for grain sorghum (GAB model at 70°C)

To fit the experimental data to various selected equations, an iterative non-linear regression procedure was applied using a statistical computer programme called COSTAT. To calculate monolayer moisture content values for BET and GAB models, the least square procedures was used. The common parameters to test the goodness of fit are mean relative percentage difference (Adrieu et al., 1985; Chen and Morey, 1989a; 1989b; Mazza and Jayas, 1991; Iglesias and Chirife, 1982) and the standard error of estimate of EMC (Ajibola, 1986; Akiritidis et al., 1988; Osborn et al., 1989; Chen and Morey, 1989a; Mazza and Jayas, 1991; Sonkhasanj et al., 1986; Madamba et al., 1993). Cervantes et al., (1993) used the root mean square while others like Maroulis et al. (1988), Tsami et al. (1990) and Madamba et al. (1993) used the F ratio. Pappas and Rao (1987) have shown that the regression coefficient is not a true representative of goodness of fit when non-linear regression is used. To calculate the goodness of fit of the selected sorption models as applied to the experimental sorption data, the mean relative percentage deviation in modulus, E(%), and variance of regression, v were selected and presented as Equations 4.1 and 4.2, respectively.

$$E(\%) = \frac{100}{n} \sum_{i=1}^{n} \frac{\epsilon_i}{X_{i\,observed}} \quad \ldots\ldots \quad 4.1$$

Where n is the number of values and $\epsilon_i = X_{i(observed)} - X_{i(predicted)}$, the absolute value. For the study n = 9.

$$V=\sum_{i=1}^{n}\frac{[X_i(predicted)-X_i(observed)]^2}{n-1} \quad 4.2$$

The above statistical information in conjunction with the mean, adequately and precisely defines the degree of success of the proposed isotherm equation (Iglesias and Chirife, 1982). The smaller the values of E(%) and v , the better the fit. From published literature, acceptable values of v should be less than 0.3. E (%) values as high as 40.94 have been published, but it should be noted that many authors have accepted E(%) values equal to 15 or less. All computed parameters and constants were rounded to four decimal places. In order to develop a single empirical model which could fit the sorption experimental data for grain sorghum, backwards multiple regression analysis was used. This empirical model is expressed as:

$$M=0.3093+0.0307RH+0.1588RH^2-8.2846\times10^{-4}T \quad 4.3$$

Where M = moisture content (db) in decimal ,
RH = relative humidity and T = absolute temperature in Kelvin for desorption process, with R' = 0.9586; and

$$M=0.3533-0.0305RH+0.2061RH^2-9.3943x10^{-4}T \quad 4.4$$

for adsorption process, with R' = 0.9639.

Tables 4.9 to 4.15 give a summary of analysis of sorption data according to various models.

Table 4.9. shows the analysis of sorption data by Oswin model (Equation 2.4). Values of parameter A decrease with increase in temperature. Besides, desorption values are higher than adsorption values at each particular temperature. Parameter B values increase with increase in temperature, with adsorption values being higher than desorption values except at 25°C . Oswin model fitted experimental data best at 70°C (desorption), as reflected by small values of E(%) and v. The poorest fit was at 25°C (desorption). This model fitted experimental data better at higher temperatures. Overall, the model fitted desorption data (mean e(%) = 9.7749) better than adsorption process (Mean E(%) =10.2173).

Table 4.9 Analysis of sorption data by Oswin Model(Equation 2.4)

TEMPERATURE, °C, AND SORPTION PROCESS	PARAMETER		E(%)	v x 10^{-4}
	A	B		
25 - Des.	0.1266	0.1888	13.6939	3.8608
25 - Ads.	0.1250	0.1789	7.4889	2.0556
40 - Des.	0.1165	0.2377	9.0776	1.2778
40 - Ads.	0.1074	0.2554	7.8211	1.0563
55 - Des.	0.1046	0.2797	10.3766	1.4403
55 - Ads.	0.0909	0.3050	12.7125	1.3103
70 - Des.	0.0779	0.3681	5.9513	0.2234
70 - Ads.	0.0711	0.3892	12.8467	0.6096

Table 4.10 shows the analysis of sorption data by Smith model (Equation 2.5). Parameter A decreases with decrease in temperature, with desorption values being higher than adsorption values except at 25°C. Parameter B values generally increase with increase in temperature but no clear trend can be observed between adsorption and desorption processes. The best fit is observed at 70°C (desorption) while the poorest is at 25°C (desorption). The higher the temperature the better the fit. Overall, the model fitted adsorption data (Mean E(%) = 9.1288) better than desorption data (Mean E(%) = 10.9313).

Table 4.10 Analysis of sorption data by Smith Model (Equation 2.5)

TEMPERATURE, °C, AND SORPTION PROCESS	PARAMETER		(E%)	$v x 10^{-4}$
	A	B		
25 - Des.	0.0901	0.0449	16.3201	5.5087
25 - Ads.	0.0928	0.0408	7.9486	2.3625
40 - Des.	0.0717	0.0562	10.9930	2.0635
40 - Ads.	0.0622	0.0570	7.9796	1.2789
55 - Des.	0.0550	0.0628	10.0085	1.5866
55 - Ads.	0.0417	0.0620	11.3398	1.1453
70 - Des.	0.0283	0.0664	6.4037	0.2254
70 - Ads.	0.0200	0.0673	9.2473	0.3229

Table 4.11 Shows the analysis of sorption data by Henderson model (Equation 2.3). Parameter A values increase with increase in temperature, with adsorption values being higher that desorption values. Parameter B values decrease with increase in temperature with desorption values being generally higher than adsorption values. This trend is opposite to that of Smith and Oswin Models. This could be explained by the fact that Henderson model, unlike the other two, has a distinct temperature term. Henderson Model fitted experimental data best at 40°C (desorption). Overall, the model fitted desorption data (Mean E(%)=5.5054) better than adsorption data (Mean E(%)= 5.5612).

Table 4.11: Analysis of sorption data by Henderson Model (Equation 2.3)

TEMPERATURE, °C, AND SORPTION PROCESS	PARAMETER		E(%)	$v \times 10^{-4}$
	A	B		
25 - Des.	0.4844	2.5809	6.6066	1.4387
25 - Ads.	0.8059	2.8206	8.9066	2.3065
40 - Des.	0.2394	2.1721	2.6889	0.2663
40 - Ads.	0.1913	1.9851	4.8692	0.4267
55 - Des.	0.1334	1.8229	5.1305	0.3782
55 - Ads.	0.1120	1.6361	3.4473	0.1099
70 - Des.	0.0691	1.3645	7.5957	0.4511
70 - Ads.	0.0620	1.2735	5.0218	0.1668

Table 4.12 shows the analysis of sorption data by Halsey Model (Equation 2.2). The model has a distinct temperature term. Parameters A and B follows the same trend like those of Henderson Model. Halsey Model fits the experimental data best at 25°C (adsorption). Overall, the model fitted desorption data (mean E(%)=14.4787) better than adsorption data (Mean E(%)=15.3058).

Table 4.12 : Analysis of sorption data by Halsey Model (Equation 2.2)

TEMPERATURE, °C, AND SORPTION PROCESS	PARAMETER		E(%)	$v x 10^{-4}$
	A	B		
25 - Des.	0.0126	4.6817	17.3896	5.8068
25 - Ads.	0.0080	4.8664	8.5371	2.5307
40 - Des.	0.0828	3.6504	13.5353	2.7505
40 - Ads.	0.1066	3.4074	11.9573	2.1958
55 - Des.	0.2021	3.1057	15.2392	2.8460
55 - Ads.	0.2355	2.8627	19.0710	2.6681
70 - Des.	0.5660	2.3643	11.7507	0.8124
70 - Ads.	0.6260	2.2459	21.6577	1.4870

Table 4.13 shows the analysis of sorption data by BET model (Equation 2.1). The magnitude of constant C increases with increase in temperature. The mono-layer moisture content values also increase with increase in temperature. This model fitted experimental data best at 70°C (adsorption) while the poorest fit was at 40°C (desorption). Over the water activity range tested, the fitting ability of the BET model was poor. This can be explained by the fact that, the BET is known to fit sorption data over a narrow water activity range of up to 0.5.

Table 4.13: Analysis of Sorption Data By BET Model (Equation 2.1)

TEMPERATURE, °C, AND SORPTION PROCESS	CONSTANT		E(%)	v
	C	M_m		
25 - Des.	-1.7546	0.0121	85.2601	0.0177
25 - Ads.	-1.7557	0.0118	84.3069	0.0166
40 - Des.	-2.1867	0.0187	89.2567	0.0220
40 - Ads.	-2.2565	0.0180	74.6377	0.0135
55 - Des.	-2.4914	0.0197	57.3829	0.0089
55 - Ads.	-2.6590	0.0183	58.9144	0.0069
70 - Des.	-3.0277	0.0189	49.2328	0.0037
70 - Ads.	-3.4826	0.0184	53.6609	0.0035

Table 4.14 shows the analysis of sorption data by GAB model (Equation 2.6). The model has three constant C_1, K and M_m (the mono-layer moisture content). M_m vales, unlike in the case of BET model, decreased with increase in temperature. In addition, the values calculated from GAB model were higher than those of BET model. Similar observations were reported by Labuza et al. (1985) working on fish flour and corn meal, Lagoudaki and Demertzis (1993) working on several different foods and Van den Berg et al. (1975) working on starch. The GAB model fitted data best at 40°C (adsorption) while the poorest fit was at 25°C (adsorption). Overall, the model fitted desorption data (Mean E(%) = 3.7261) better than adsorption data (Mean E(%)=4.0515).

Table 4.14: Analysis of sorption data by GAB Model (Equation 2.6)

TEMPERATARE, °C, AND SORPTION PROCESS	CONSTANT			E (%)	$vx10^{-4}$
	C	K	M_M		
25 - Des.	13.4888	0.5972	0.1025	4.2334	1.0117
25 - Ads.	400.8420	0.6772	0.0780	5.6060	1.5765
40 - Des.	15.4254	0.6592	0.0867	3.0739	0.4622
40 - Ads.	25.6977	0.7359	0.0688	2.9783	0.2575
55 - Des.	13.7285	0.7438	0.0703	4.1059	0.4324
55 - Ads.	9.2780	0.7672	0.0619	3.0336	0.1199
70 - Des.	11.8568	0.8111	0.0506	3.4910	0.3385
70 - Ads.	4.8965	0.8030	0.0530	4.5879	0.2277

Table 4.15 shows the analysis of sorption data by present author's Empirical model (Equation 4.3 and 4.4). This model fitted experimental data best at 25°C (desorption) and had the poorest fit at 70°C (adsorption). Overall, the Empirical model fitted desorption data (Mean E(%) = 6.4061) better than adsorption data (Mean E(%)=7.2756).

Table 4.15: Analysis of sorption data by Epirical Model (Equations 4.3 and 4.4)

TEMPERATURE, °C, AND SORPTION PROCESS	E(%)	$v \times 10^{-4}$
25 - Des.	5.2756	1.4819
25 - Ads.	6.7367	2.2523
40 - Des.	6.2657	0.9527
40 - Ads.	6.2534	0.6253
55 - Des.	5.6171	1.0674
55 - Ads.	5.4075	0.5153
70 - Des.	8.4658	2.4001
70 - Ads.	10.7049	1.5348

ANOVA on mean percentage difference proved that the difference between models was significant at 5% level of significance. Duncan multiple range test proved the BET model to be significantly different from the rest. Halsey model was significantly different from Henderson and GAB models. The ranking based on order of best fit was as follows: 1. GAB; 2. Henderson; 3. Empirical; 4. Oswin; 5. Smith; 6. Halsey; 7 BET.

Comparison between the empirical model and the other models indicated that only the GAB model was significantly superior to the empirical model. This shows that empirical model can successfully predict EMC, mainly for engineering purposes where a simple and accurate model is required rather than a sophisticated theoretical model. However, this model is absolutely conditions and product specific. The GAB model was exceptionally superior to other models. This is in line with research findings reported by Mazza and Jayas (1991) Cervantes et al. (1993), Maroulis et al. (1988), Tsami et al. (1990), Mok and Hattiarachchy (1990) and Schuchmann et al. (1990). GAB model's superiority has made it to be adopted by European COST 90 Group on water activity.

4.2 Drying Experiments

Appendix B shows the average thin layer drying data for two test samples of each sorghum variety. Figures 4.13 to 4.26 show the drying curves for the different varieties. The drying air conditions are shown in brackets. Initial moisture content of grains is also indicated in brackets as part of the legend. The drying curves indicate that the drying rate depends on drying air temperature. The higher the temperature the higher the drying rate. At every drying temperature, rate of moisture removal is faster at initial stages and decreases with time until equilibrium is reached.

The EMC values used in the analysis of drying data were given by the asymptotic Value of the drying curve. The model parameters were computed by an iterative non-linear regression technique using COSTAT computer package. These parameters are summarised in Tables 4.16 to 4.22. Data from these tables reveal that k values were lower than K values at any given temperature and variety. The values of both parameter increased with increase in drying temperature. The general trend was that, both k and K were higher at high air flow rate than at low flow rate. Regression coefficients (R^2) reveal that both models fitted data for naturally moist grains better than for rewetted grains. This could be explained by the fact that rewetting of grains changes some grain characteristics such as density and bulk porosity. Rewetting is also known to decrease the magnitude of hysteresis due to molecular shrinkage and crack formation (Sun and Woods, 1993). Page model (Equation 2.31) fitted data better than Equation 2.18, a fact which can only be attributed to introduction of an extra parameter N. This is in agreement with work reported by Page (1949), Syarief et al. (1984) and Bruce (1985).

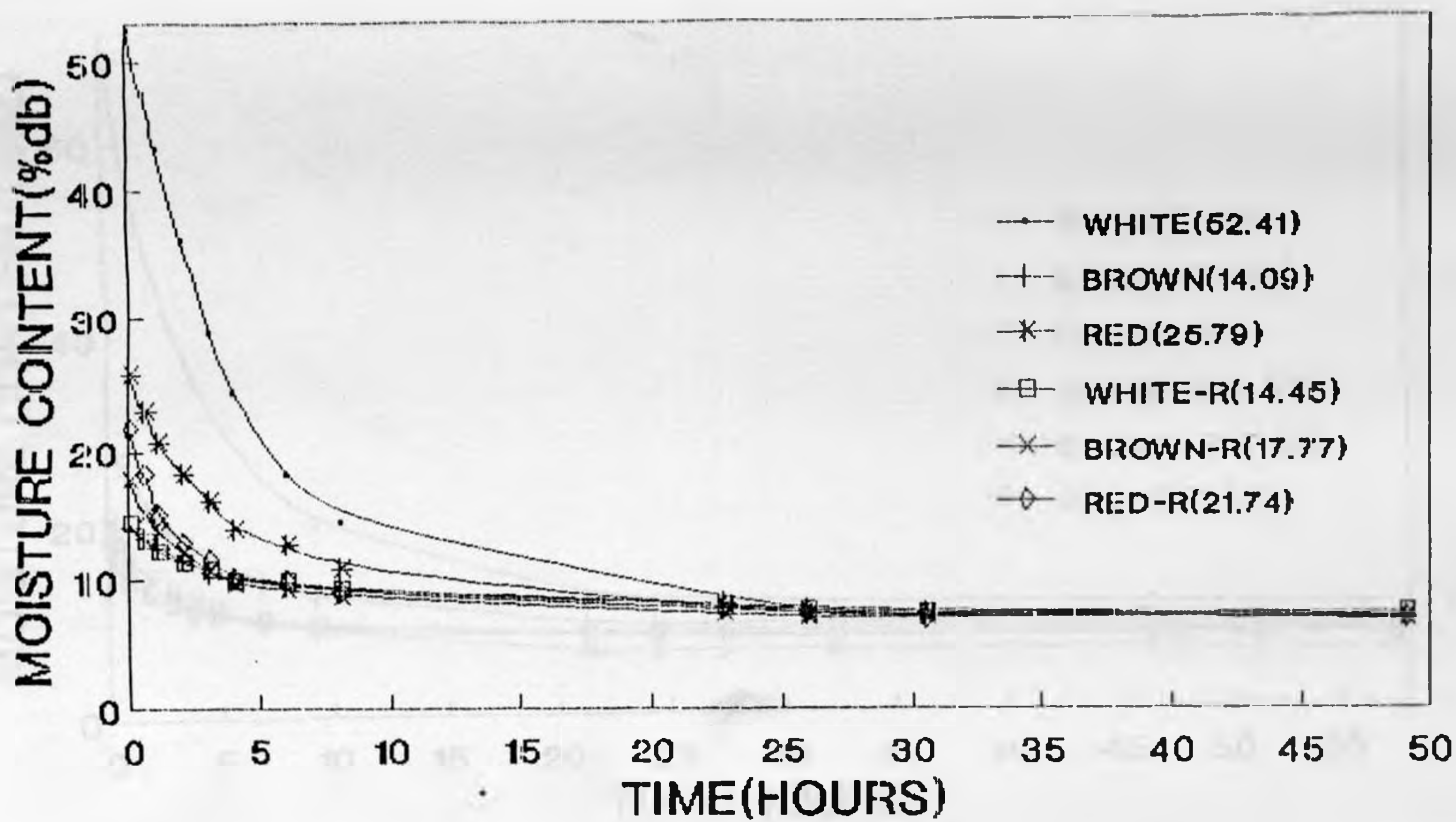


Figure 4.13 Drying curve
(T=40°C, V=1.7781 m/s, RH=35.44%)

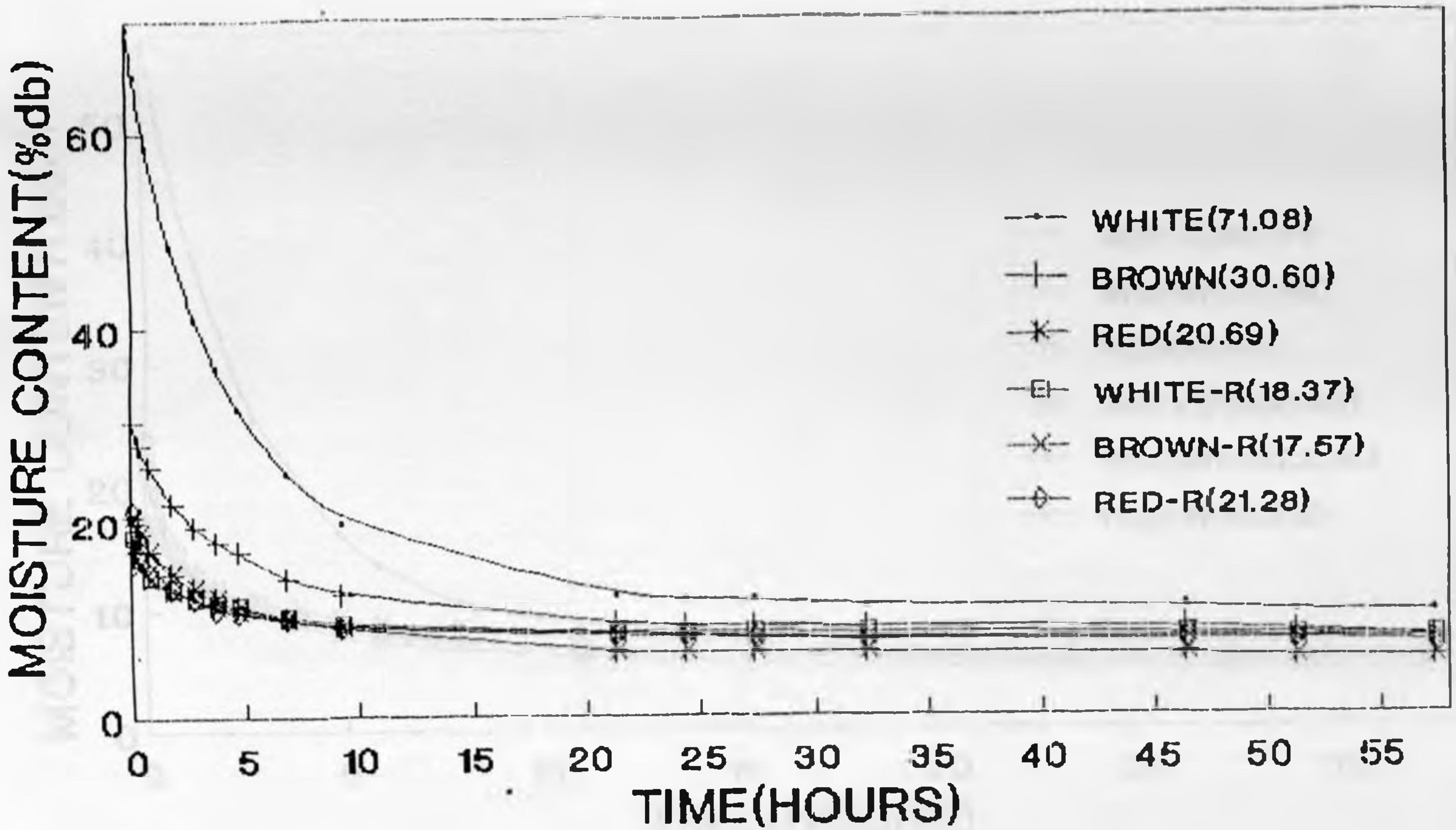


Figure 4.14 Drying curve
(T=40°C, V=0.9504 m/s, RH=37.54%)

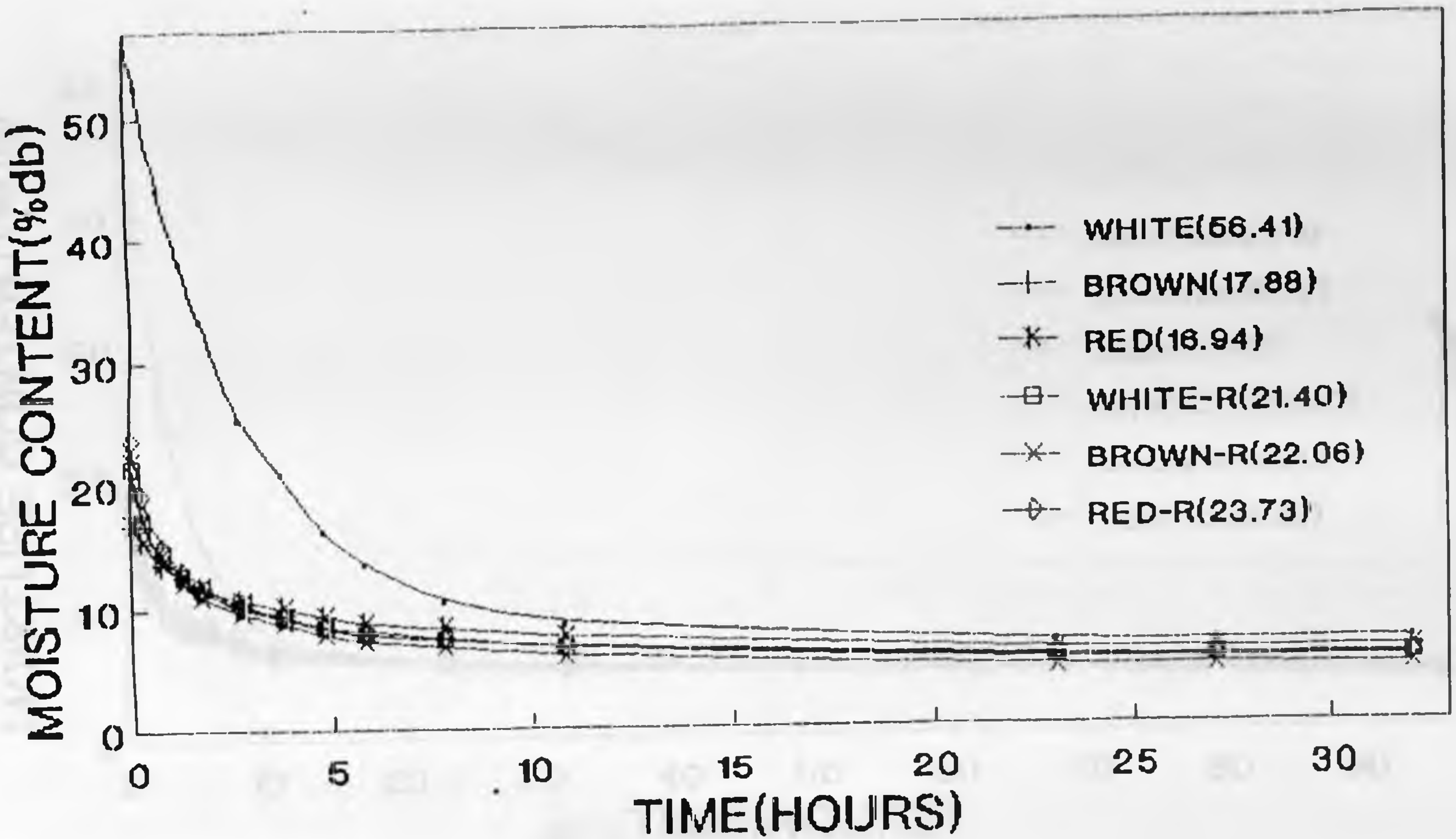


Figure 4.15 Drying curve
(T=50°C, V=1.7781 m/s, RH=34.34%)

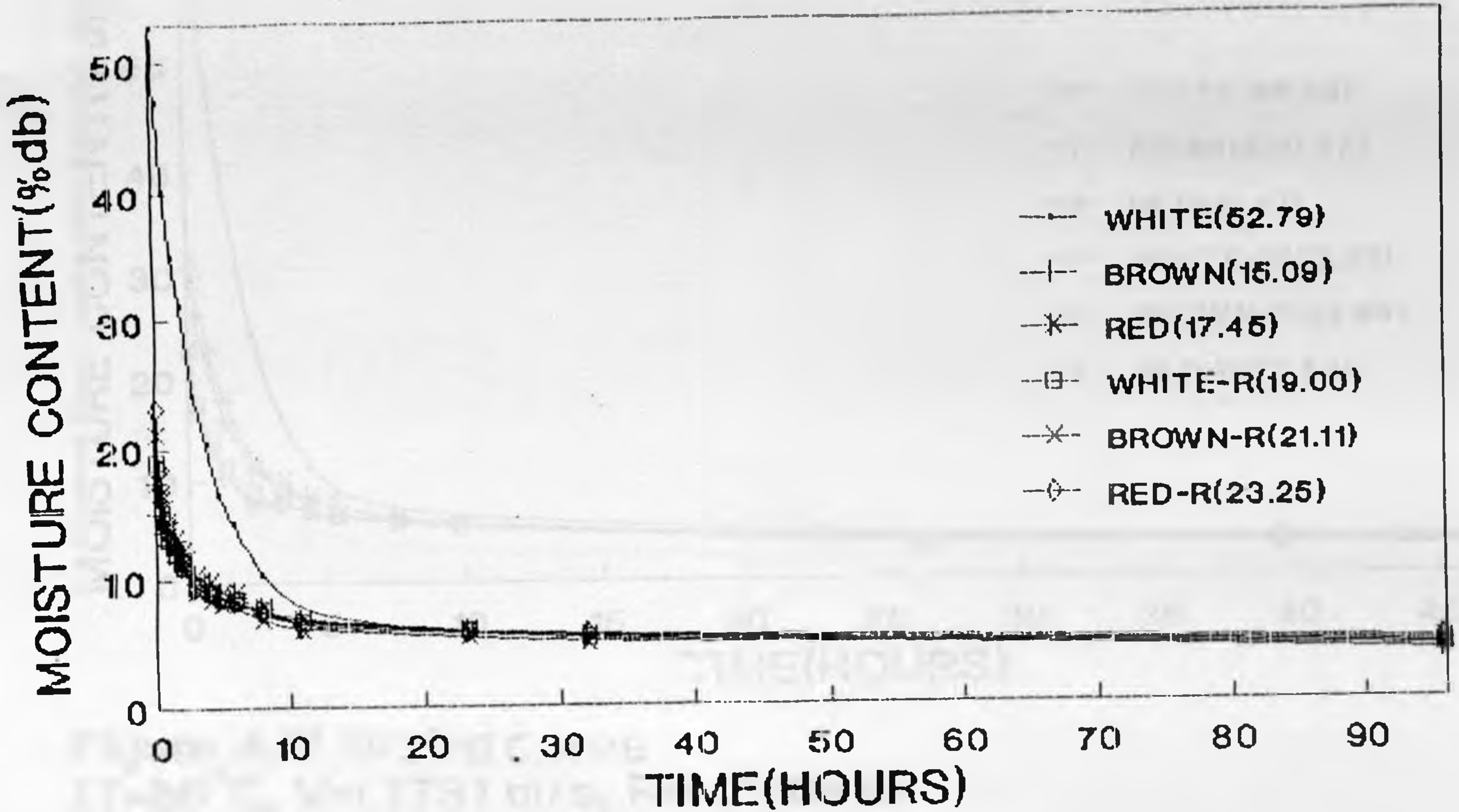


Figure 4.16 Drying curve
(T=50°C,V=0.9504 m/s, RH=34.40%)

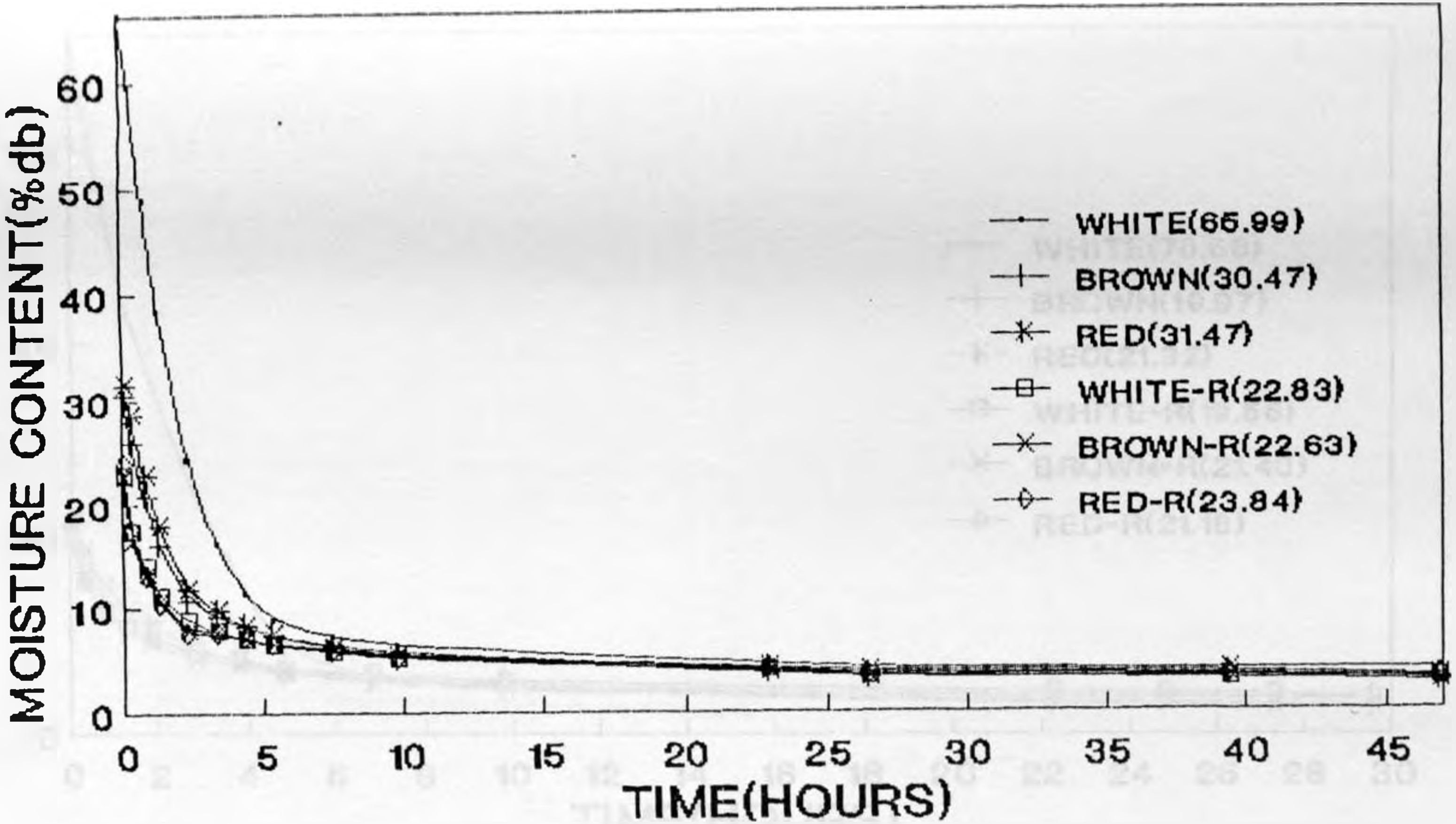


Figure 4.17 Drying curve
(T=60°C, V=1.7781 m/s, RH=29.04%)

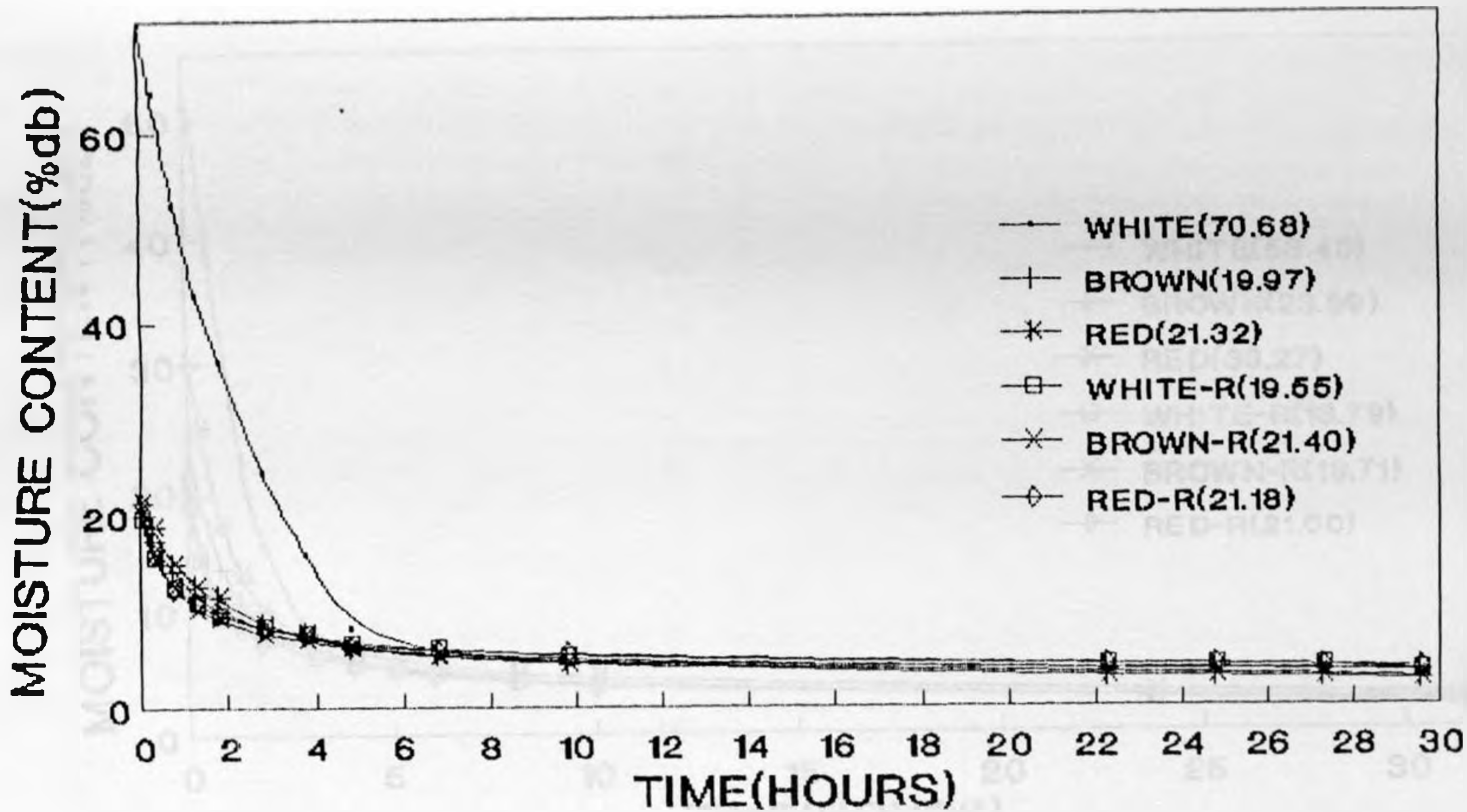


Figure 4.18 Drying curve
(T=60°C, V=0.9504 m/s,RH=28.14%)

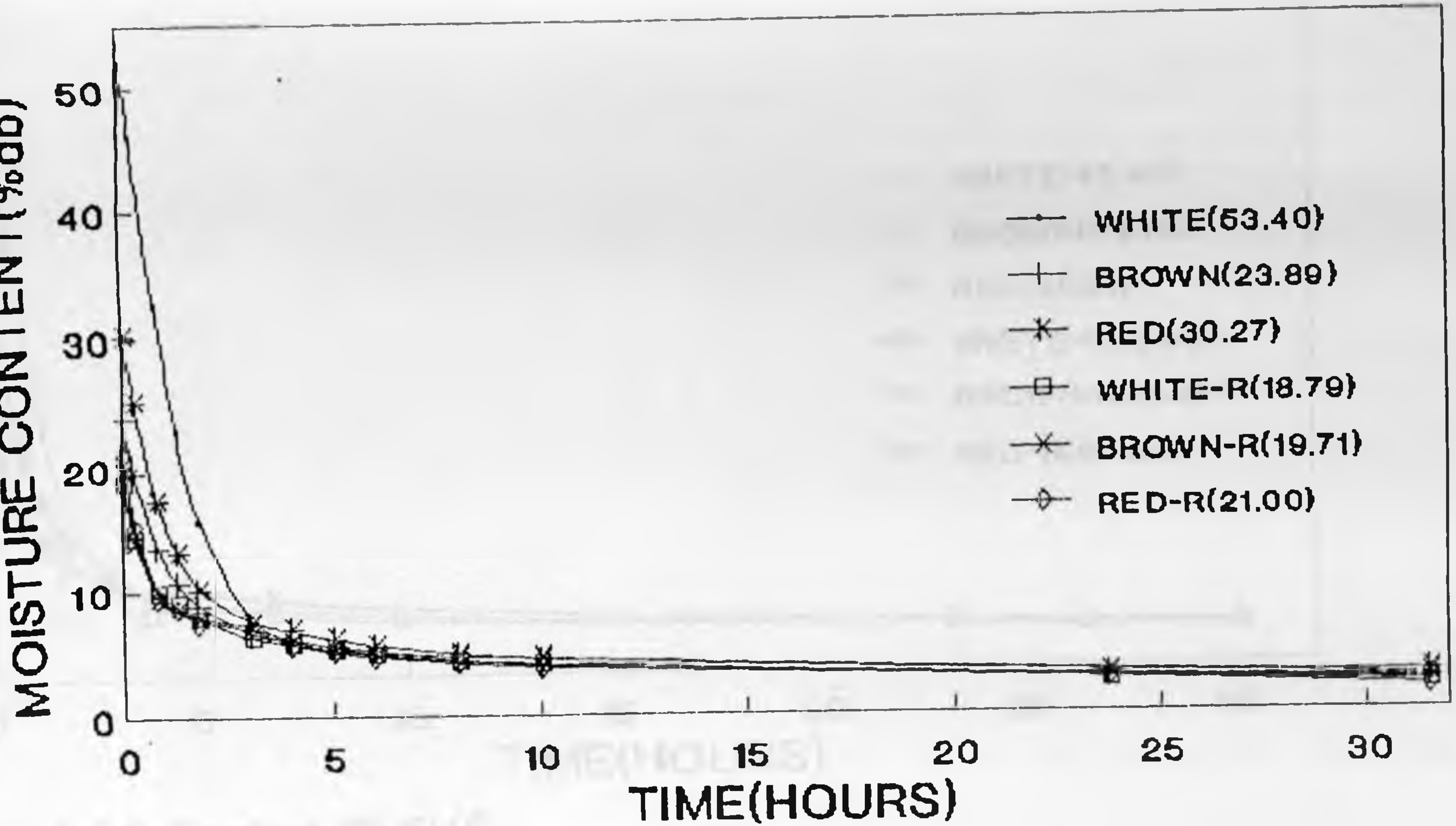


Figure 4.19 Drying curve
(T=70°C, V=1.7781 m/s,RH=30.78%)

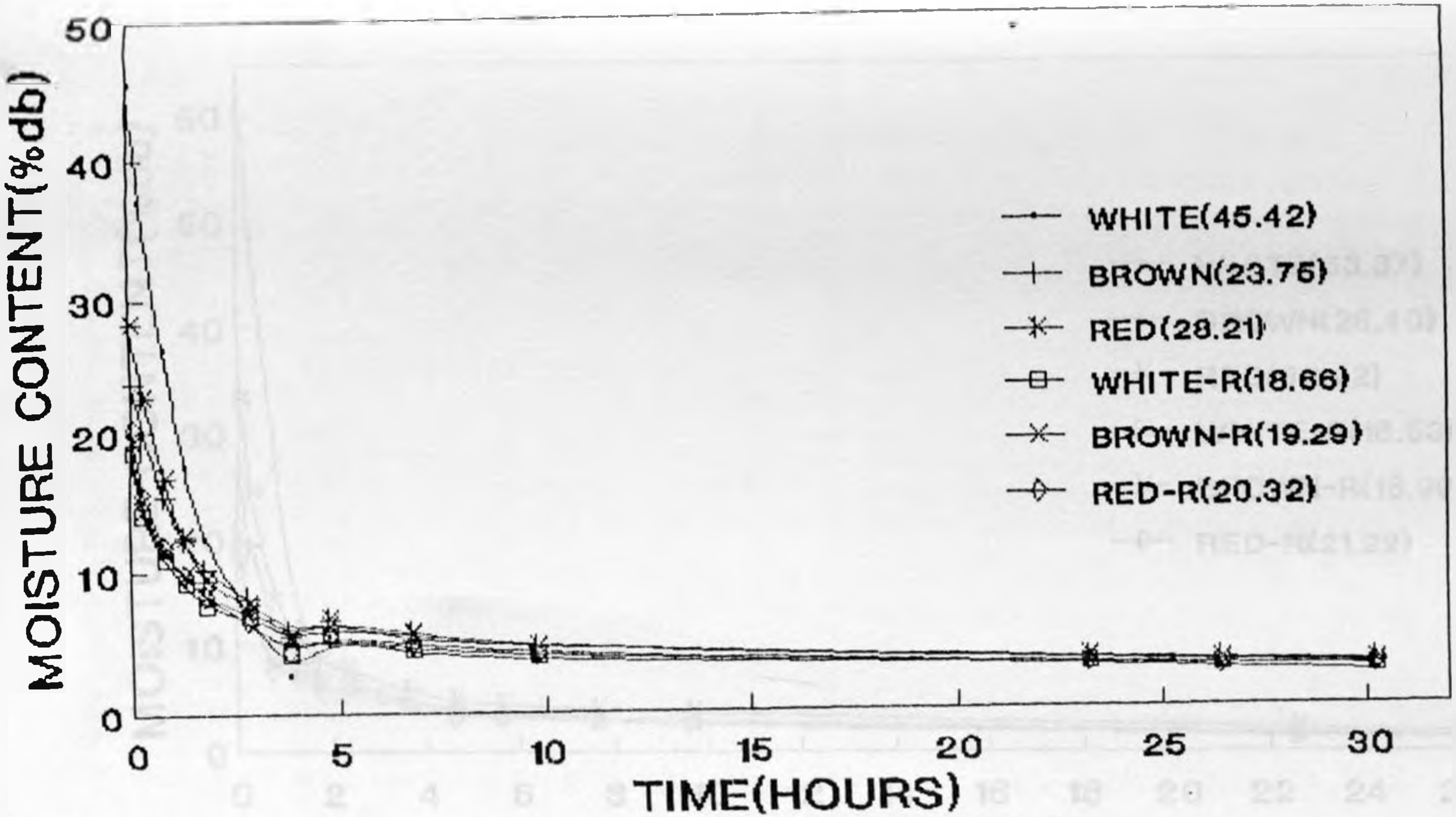


Figure 4.20 Drying curve
(T=70°C, V=0.9504 m/s, RH=32.25%)

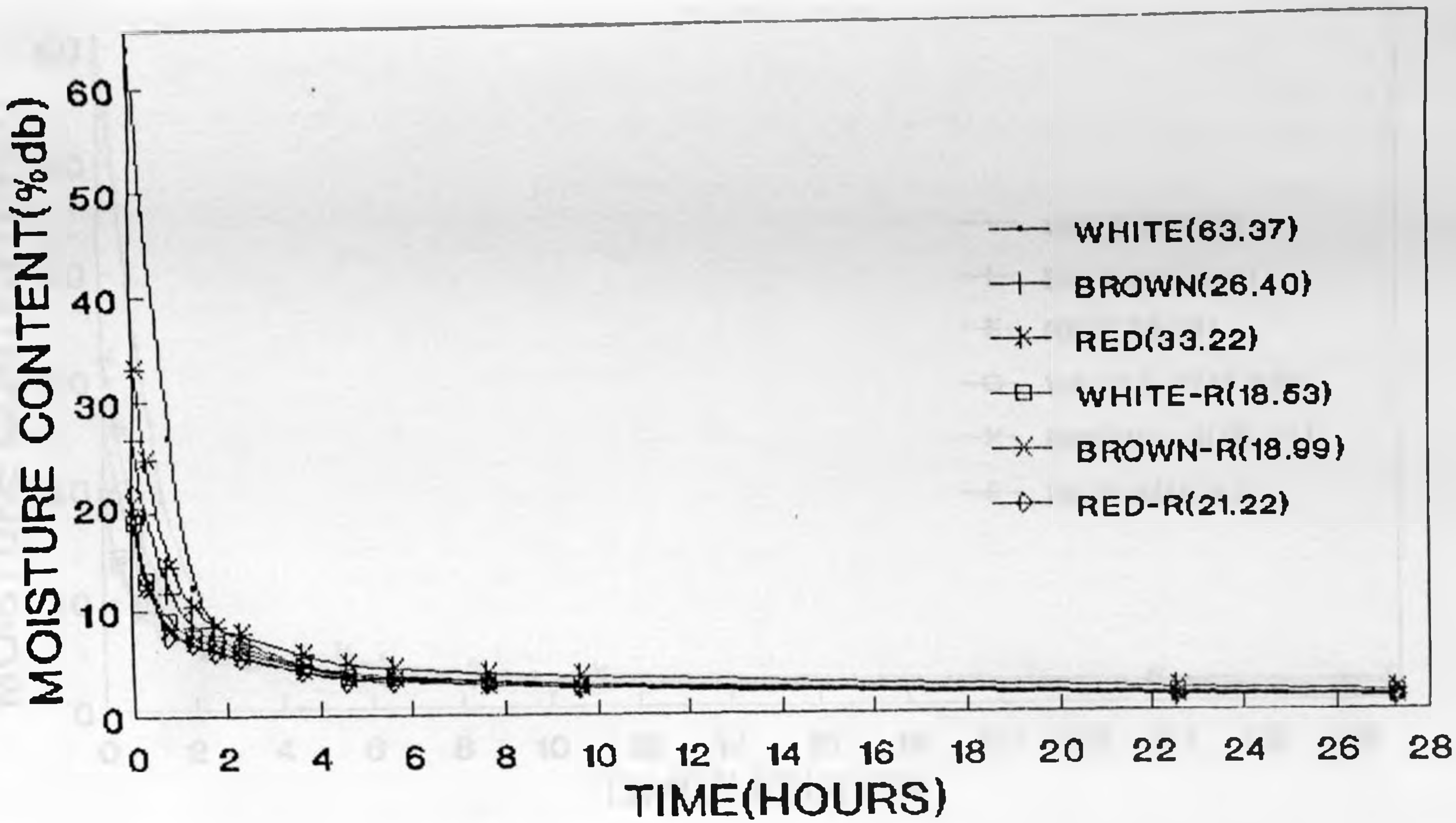


Figure 4.21 Drying Curve
(T=80°C,V=1.7781 m/s, RH=28.61%)

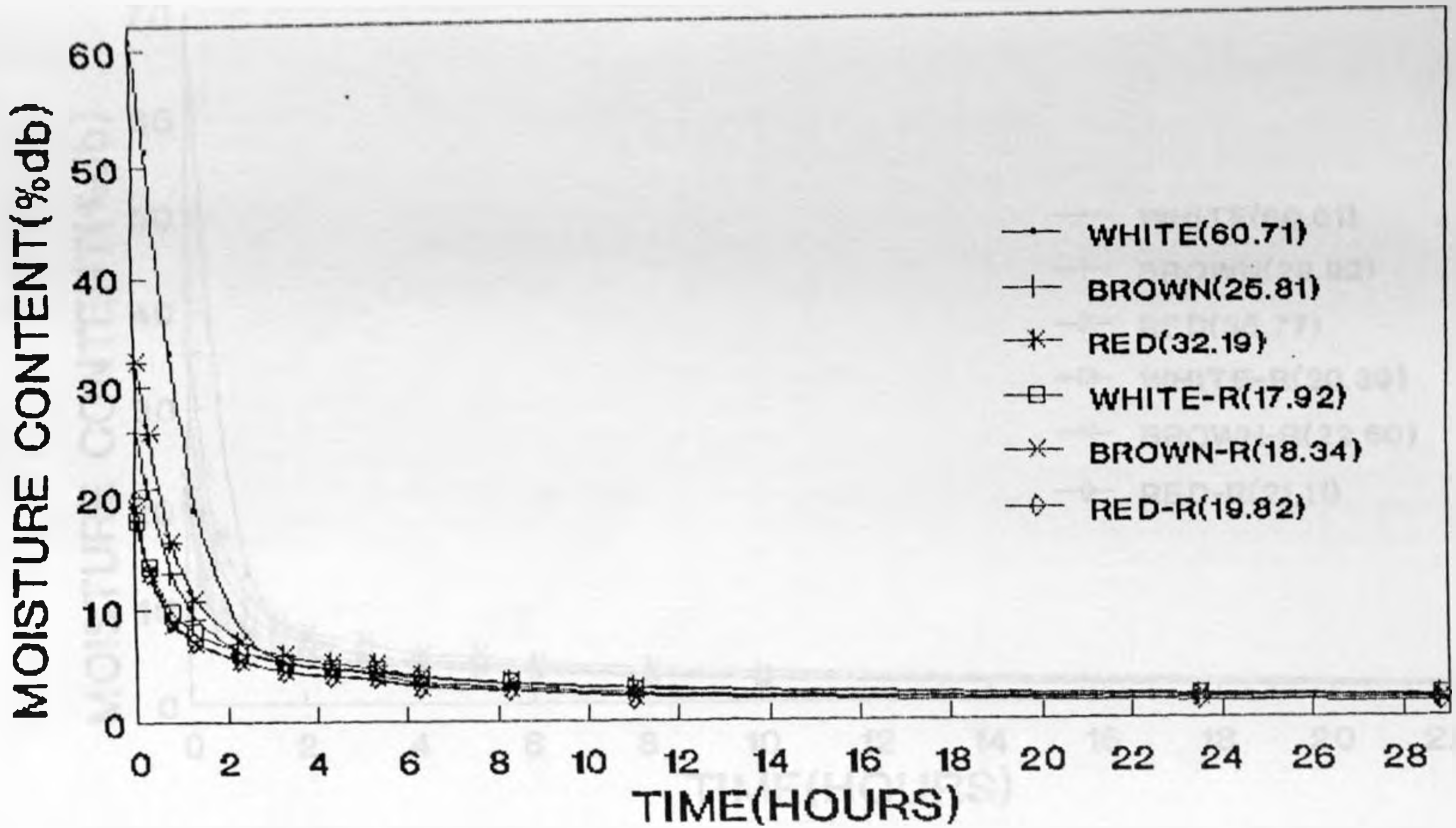


Figure 4.22 Drying curve
(T=80°C,V=0.9504 m/s,RH=30.80%)

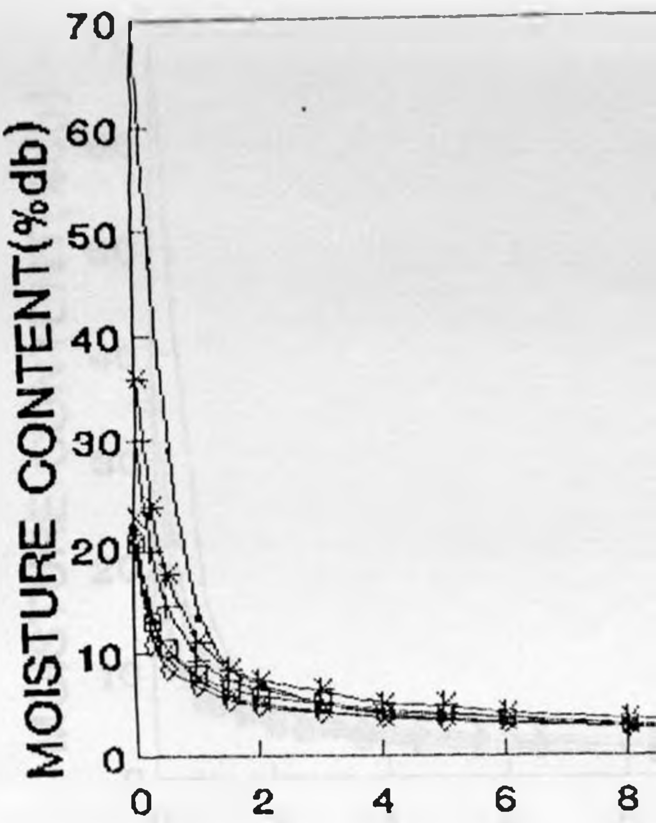
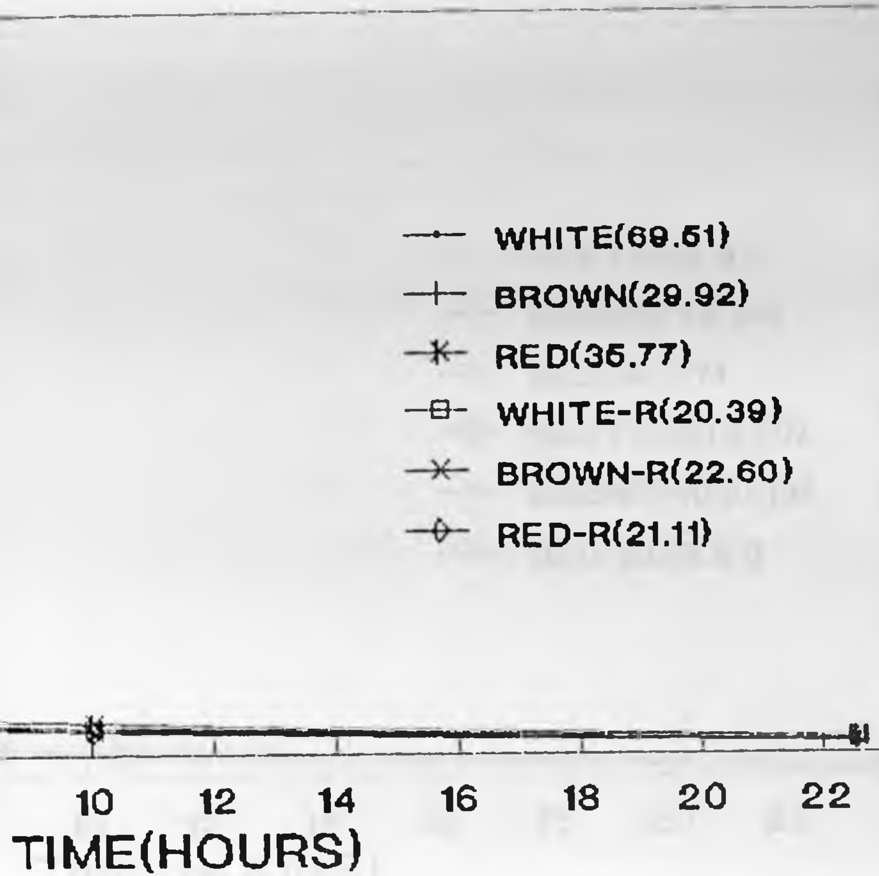


Figure 4.23 Drying curve
(T=90°C,V=1.7781 m/s,RH=


WHITE(69.51)
BROWN(29.92)
RED(35.77)
WHITE-R(20.39)
BROWN-R(22.60)
RED-R(21.11)
10
12
14
16
18
20
22
TIME(HOURS)

-31.88%)

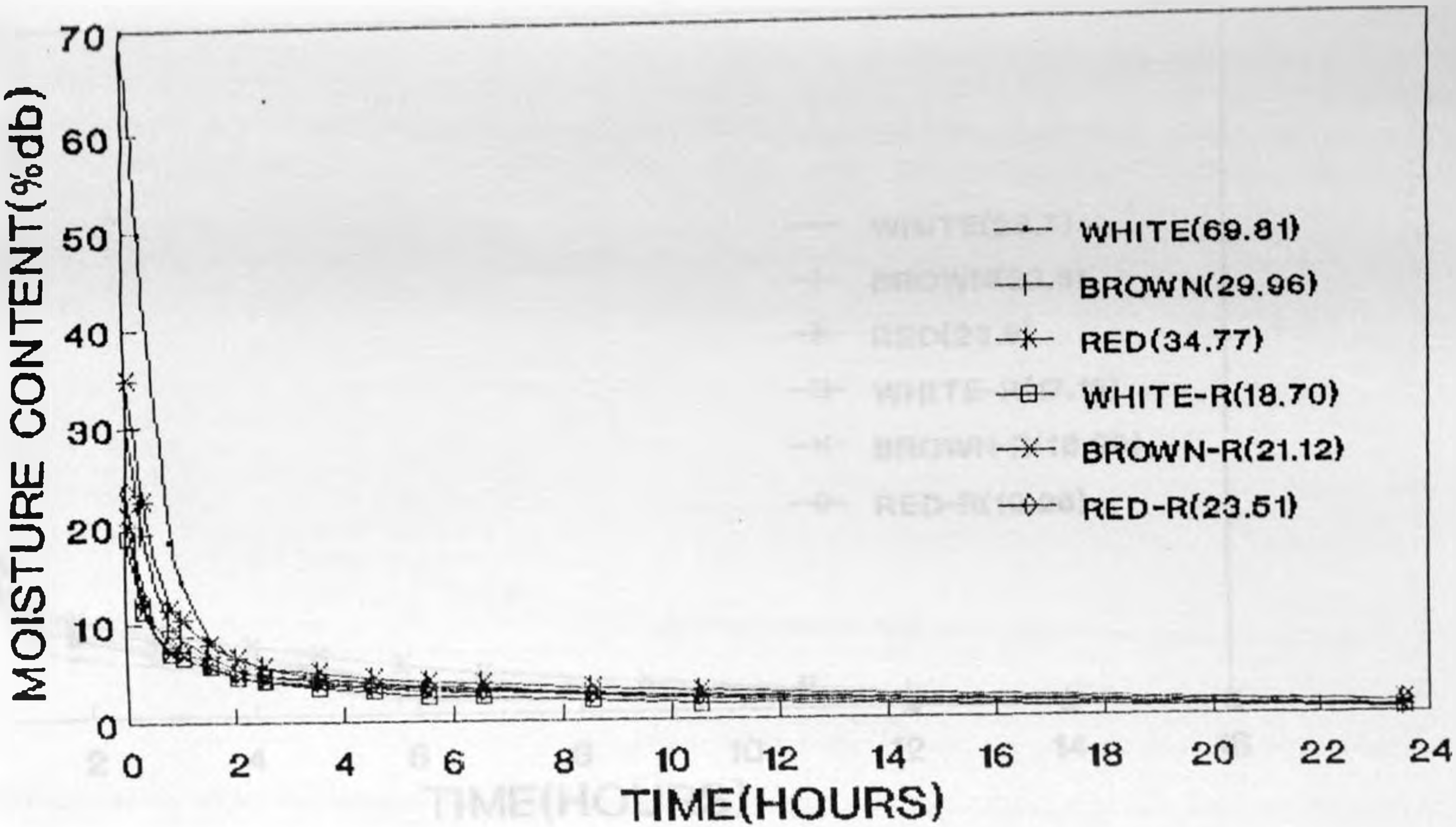


Figure 4.24 Drying curve
(T=90°C,V=0.9504 m/s,RH=29.13)

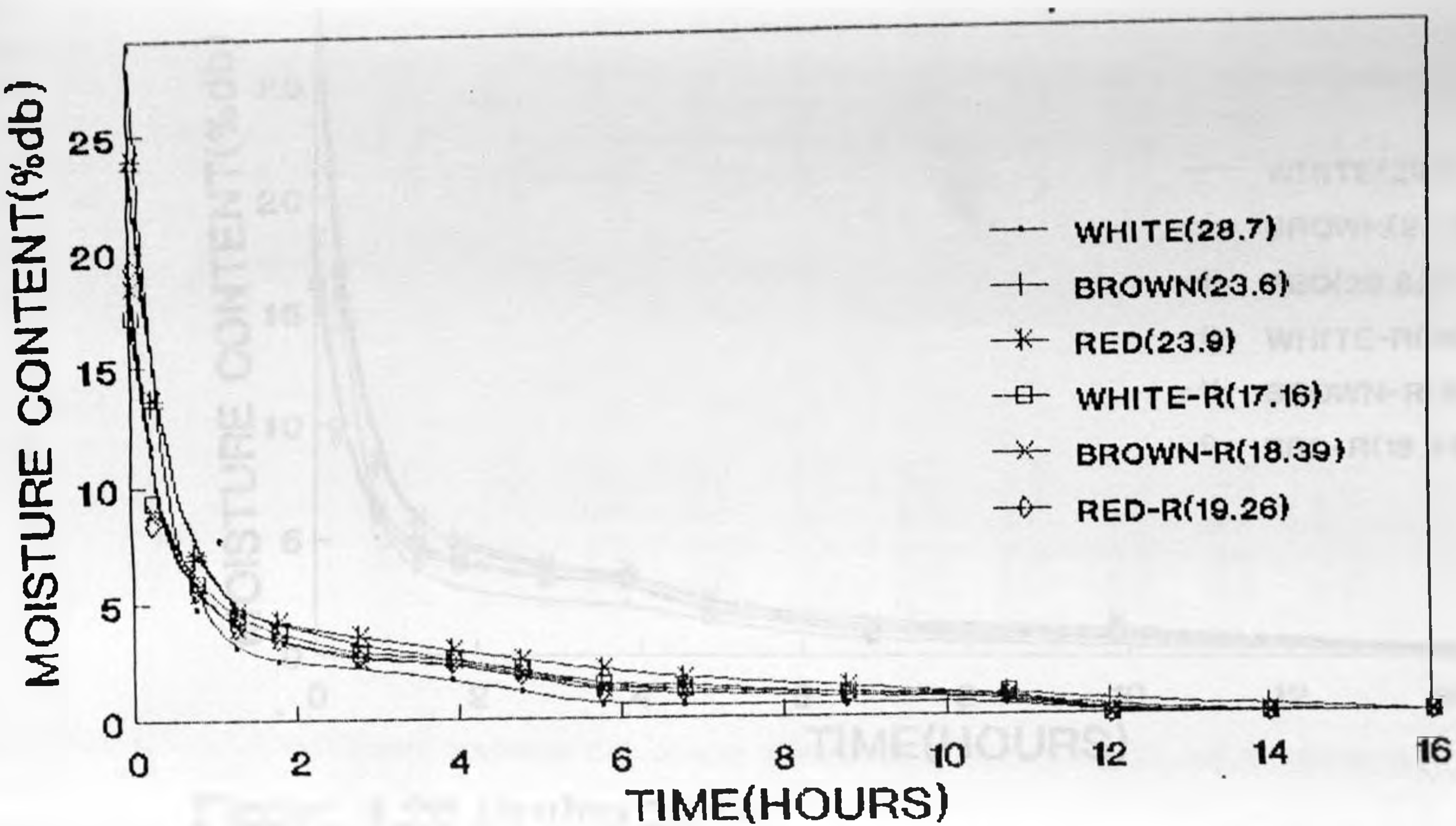


Figure 4.25 Drying curve
(T=100°C,V=1.7781 m/s,RH=35.84)

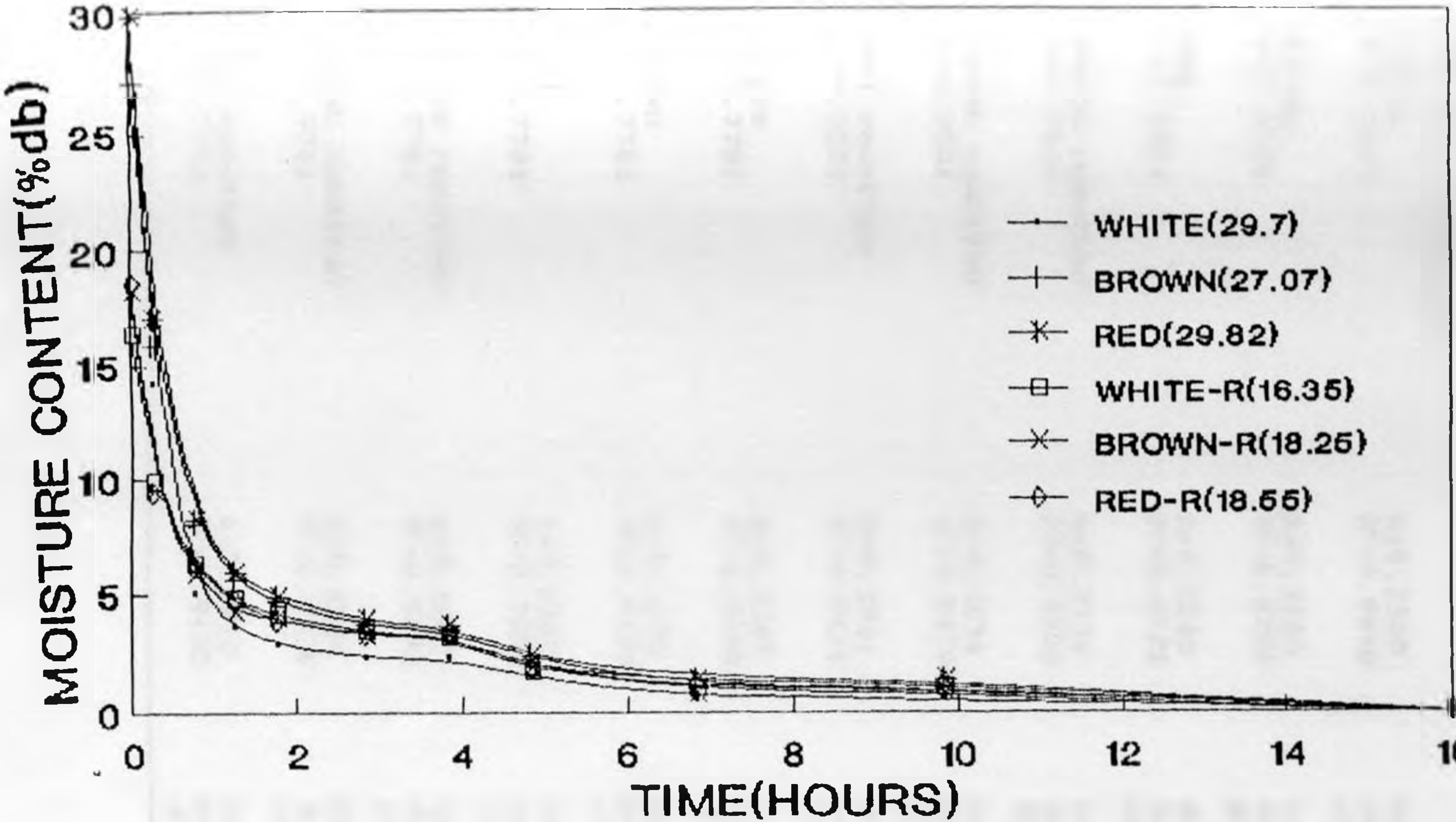


Figure 4.26 Drying curve
(T=100°C,V=0.9594.m/s,RH=39.47)

Table 4.16 Models' Parameters at 40°C

Variety and Air flow rate(m/s)	MR=Exp(-kt)	MR=Exp(-Kt^N)
White V=0.9504	k=0.2300 R^2=0.9948	K=0.2933 N=0.8202 R^2=0.9997
Brown V=0.9504	k=0.2150 R^2=0.9796	K=0.3266 N=0.6935 R^2=0.9976
Red V=0.9504	k=0.2245 R^2=0.9721	K=0.3569 N=0.6608 R^2=0.9988
White rewetted V=0.9504	k=0.3134 R^2=0.9302	K=0.5357 N=0.5418 R^2=0.9970
Brown rewetted V=0.9504	k=0.2834 R^2=0.9439	K=0.4839 N=0.5703 R^2=0.9977
Red rewetted V=0.9504	k=0.3931 R^2=0.9411	K=0.5989 N=0.5535 R^2=0.9961
White V=1.7781	k=0.2347 R^2=0.9990	K=0.2329 N=1.0059 R^2=0.9990
Brown V=1.7781	k=0.1870 R^2=0.9575	K=0.2915 N=0.6684 R^2=0.9893
Red V=1.7781	k=0.2312 R^2=0.9886	K=0.3044 N=0.7827 R^2=0.9979
White rewetted V=1.7781	k=0.2347 R^2=0.9493	K=0.3766 N=0.6333 R^2=0.9936
Brown rewetted V=1.7781	k=0.3546 R^2=0.9736	K=0.4769 N=0.6974 R^2=0.9964
Red rewetted V=1.7781	k=0.4216 R^2=0.9605	K=0.5602 N=0.6533 R^2=0.9919

Table 4.17 Models' Parameters at 50°C

Variety and Air flow rate(m/s)	MR=Exp(-kt)	$MR=Exp(-Kt^N)$
White V=0.9504	k=0.3049 R^2=0.9898	K=0.3769 N=0.8128 R^2=0.9987
Brown V=0.9504	k=0.1781 R^2=0.8982	K=0.3397 N=0.5545 R^2=0.9923
Red V=0.9504	k=0.2286 R^2=0.9417	K=0.3686 N=0.6277 R^2=0.9918
White rewetted V=0.9504	k=0.3415 R^2=0.8024	K=0.6065 N=0.4387 R^2=0.9962
Brown rewetted V=0.9504	k=0.4569 R^2=0.8586	K=0.6860 N=0.4778 R^2=0.9949
Red rewetted V=0.9504	k=0.5251 R^2=0.8770	K=0.7250 N=0.4958 R^2=0.9920
White V=1.7781	k=0.3522 R^2=0.9994	K=0.3662 N=0.9617 R^2=0.9997
Brown V=1.7781	k=0.3315 R^2=0.9475	K=0.4911 N=0.6386 R^2=0.9979
Red V=1.7781	k=0.2880 R^2=0.9575	K=0.4247 N=0.6730 R^2=0.9973
White rewetted V=1.7781	k=0.4933 R^2=0.9236	K=0.6802 N=0.5710 R^2=0.9988
Brown rewetted V=1.7781	k=0.5421 R^2=0.9113	K=0.7289 N=0.5465 R^2=0.9986
Red rewetted V=1.7781	k=0.5913 R^2=0.9315	K=0.7438 N=0.5770 R^2=0.9971

Table 4.18 Models' Parameters at 60°C

Variety and Air flow rate(m/s)	MR=Exp(-kt)	$MR=Exp(-Kt^N)$
White V=0.9504	k=0.4284 R^2=0.9981	K=0.4066 N=1.0645 R^2=0.9986
Brown V=0.9504	k=0.4613 R^2=0.9734	K=0.5724 N=0.6987 R^2=0.9969
Red V=0.9504	k=0.4001 R^2=0.9755	K=0.5099 N=0.7102 R^2=0.9973
White rewetted V=0.9504	k=0.4976 R^2=0.9186	K=0.6794 N=0.5389 R^2=0.9978
Brown rewetted V=0.9504	k=0.6730 R^2=0.9325	K=0.8129 N=0.5522 R^2=0.9987
Red rewetted V=0.9504	k=0.6267 $R^2$0.9163=	K=0.7911 N=0.5237 R^2=0.9983
White V=1.7781	k=0.4791 R^2=0.9983	K=0.4632 N=1.0460 R^2=0.9986
Brown V=1.7781	k=0.4855 R^2=0.9670	K=0.5972 N=0.6982 R^2=0.9901
Red V=1.7781	k=0.4347 R^2=0.9821	K=0.5062 N=0.8045 R^2=0.9902
White rewetted V=1.7781	k=0.5568 R^2=0.9182	K=0.7360 N=0.5383 R^2=0.9965
Brown rewetted V=1.7781	k=0.6329 R^2=0.8810	K=0.8105 N=0.4739 R^2=0.9931
Red rewetted V=1.7781	k=0.6983 R^2=0.8897	K=0.8342 N=0.4850 R^2=0.9884

Table 4.19 Models' Parameters at 70°C

Variety and Air flow rate(m/s)	MR=Exp(-kt)	MR=Exp(-Kt^N)
White V=0.9504	k=0.8177 R^2=0.9944	K=0.8204 N=0.9854 R^2=0.9944
Brown V=0.9504	k=0.5770 R^2=0.9754	K=0.6626 N=0.7274 R^2=0.9928
Red V=0.9504	k=0.7226 R^2=0.9695	K=0.7875 N=0.7034 R^2=0.9874
White rewetted V=0.9504	k=0.6697 R^2=0.9359	K=0.7986 N=0.5833 R^2=0.9890
Brown rewetted V=0.9504	k=0.6317 R^2=0.9119	K=0.7856 N=0.5290 R^2=0.9918
Red rewetted V=0.9504	k=0.6877 R^2=0.9521	K=0.7955 N=0.6196 R^2=0.9910
White V=1.7781	k=0.7181 R^2=0.9952	K=0.7164 N=1.0087 R^2=0.9953
Brown V=1.7781	k=0.6688 R^2=0.9464	K=0.7638 N=0.6275 R^2=0.9891
Red V=1.7781	k=0.7217 R^2=0.9701	K=0.7804 N=0.7061 R^2=0.9896
White rewetted V=1.7781	k=0.6020 R^2=0.8605	K=0.7845 N=0.4889 R^2=0.9939
Brown rewetted V=1.7781	k=0.7450 R^2=0.8124	K=0.8979 N=0.4303 R^2=0.9901
Red rewetted V=1.7781	k=0.7512 R^2=0.8235	K=0.8837 N=0.4440 R^2=0.9852

Table 4.20 Models' Parameters at 80°C

Variety and Air flow rate(m/s)	MR=Exp(-kt)	MR=Exp(-Kt^N)
White V=0.9504	k=0.9094 R^2=0.9944	K=0.9060 N=1.1428 R^2=0.9960
Brown V=0.9504	k=0.8533 R^2=0.9669	K=0.8752 N=0.6906 R^2=0.9861
Red V=0.9504	k=0.8685 R^2=0.9690	K=0.8847 N=0.7012 R^2=0.9861
White rewetted V=0.9504	k=0.6347 R^2=0.9135	K=0.7896 N=0.5545 R^2=0.9956
Brown rewetted V=0.9504	k=0.8391 R^2=0.9152	K=0.9165 N=0.5343 R^2=0.9948
Red rewetted V=0.9504	k=0.9147 R^2=0.8986	K=0.9735 N=0.4952 R^2=0.9973
White V=1.7781	k=1.2175 R^2=0.9927	K=1.2178 N=1.0022 R^2=0.9927
Brown V=1.7781	k=0.9155 R^2=0.9441	K=0.9604 N=0.5891 R^2=0.9885
Red V=1.7781	k=0.9988 R^2=0.9553	K=1.0116 N=0.6217 R^2=0.9867
White rewetted V=1.7781	k=0.7510 R^2=0.8863	K=0.8983 N=0.4921 R^2=0.9975
Brown rewetted V=1.7781	k=0.8917 R^2=0.8709	K=0.9986 N=0.4590 R^2=0.9966
Red rewetted V=1.7781	k=1.1429 R^2=0.8549	K=1.1431 N=0.4142 R^2=0.9950

Table 4.21 Models' Parameters at 90°C

Variety and Air flow rate(m/s)	$MR=Exp(-kt)$	$MR=Exp(-Kt^N)$
White V=0.9504	k=1.5736 R^2=0.9855	K=1.5610 N=0.9782 R^2=0.9854
Brown V=0.9504	k=1.2706 R^2=0.9185	K=1.1900 N=0.5041 R^2=0.9818
Red V=0.9504	k=1.2820 R^2=0.9310	K=1.2020 N=0.5290 R^2=0.9850
White rewetted V=0.9504	k=1.0389 R^2=0.8535	K=1.0901 N=0.4387 R^2=0.9954
Brown rewetted V=0.9504	k=1.1487 R^2=0.7871	K=1.1546 N=0.3661 R^2=0.9935
Red rewetted V=0.9504	k=1.3462 R^2=0.8431	K=1.2524 N=0.3895 R^2=0.9964
White V=1.7781	k=1.6500 R^2=0.9896	K=1.5619 N=0.8961 R^2=0.9907
Brown V=1.7781	k=1.2062 R^2=0.9199	K=1.1030 N=0.5238 R^2=0.9900
Red V=1.7781	k=1.2543 R^2=0.9353	K=1.1312 N=0.5507 R^2=0.9891
White rewetted V=1.7781	k=1.0274 R^2=0.8572	K=1.0320 N=0.4608 R^2=0.9976
Brown rewetted V=1.7781	k=1.3453 R^2=0.8924	K=1.1791 N=0.4634 R^2=0.9961
Red rewetted V=1.7781	k=1.6073 R^2=0.8359	K=1.2731 N=0.3823 R^2=0.9989

Table 4.22 Models' Parameters at 100°C

Variety and Air flow rate(m/s)	MR=Exp(-kt)	$MR=Exp(-Kt^N)$
White V=0.9504	k=2.4713 R^2=0.9688	K=1.7267 N=0.5380 R^2=0.9902
Brown V=0.9504	k=1.4490 R^2=0.9401	K=1.2554 N=0.5079 R^2=0.9917
Red V=0.9504	k=1.5572 R^2=0.9381	K=1.3004 N=0.4912 R^2=0.9909
White rewetted V=0.9504	k=0.9919 R^2=0.8936	K=1.0376 N=0.4675 R^2=0.9950
Brown rewetted V=0.9504	k=1.3600 R^2=0.8762	K=1.2135 N=0.4123 R^2=0.9938
Red rewetted V=0.9504	k=1.3252 R^2=0.8649	K=1.2060 N=0.3964 R^2=0.9957
White V=1.7781	k=2.9832 R^2=0.9649	K=1.8331 N=0.4608 R^2=0.9952
Brown V=1.7781	k=1.4718 R^2=0.9319	K=1.2647 N=0.4799 R^2=0.9928
Red V=1.7781	k=1.5038 R^2=0.9154	K=1.2569 N=0.4523 R^2=0.9879
White rewetted V=1.7781	k=1.2312 R^2=0.8830	K=1.1653 N=0.4410 R^2=0.9952
Brown rewetted V=1.7781	k=1.5933 R^2=0.8871	K=1.3138 N=0.4088 R^2=0.9950
Red rewetted V=1.7781	k=1.7957 R^2=0.8756	K=1.3937 N=0.3849 R^2=0.9966

The single parameter Equation 2.18 is usually recommended for testing the difference in drying rates of different products. To test the difference in sorghum varieties, ANOVA on parameter k was carried out. At low air flow rate, v=0.9504 m/s, the difference was insignificant at 5% level of significance. But at a flow rate of 1.7781 m/s the difference was significant at the same level of significance. Researchers who have reported the same results include stroshine et al. (1981) and Jayas et al., (1991).

Correlation tests showed that only drying air temperature was significantly correlated to values of parameter k. The relationship between k and drying temperature was found to be of Arrhenius type given in Equation 4.5.

$$k = C_1 \exp\left(\frac{-C_2}{T}\right) \quad \ldots\ldots\ldots \quad 4.5$$

Where C_1 and C_2 are constants depending on particular grain and T is temperature in Kelvin.

Equations of the same form as Equation 4.5. have been used by Ross and White (1972), Henderson and Pabis (1961) and chu and Hustrulid (1968). Values of the parameter in Equation 4.5. are given in Table 4.23. In this table, sorghum varieties are grouped according to the ranking of Duncans's Multiple Range test based on ANOVA on k parameter.

Table 4.23 Relationship between drying temperature and parameter k

Variety	Air flow rate (m/s)	$C_1(H^{-1})$	$C2(Kelvin^{-1})$	R^2
All	0.9504	17035.702	3481.498	0.8703
Brown,Red,White-R, Brown-R	1.7781	12634.293	3371.257	0.9225
White,Red-R	1.7781	63056.281	3841.573	0.9100

To test the relationship between drying conditions and parameters K and N of Page model (Equation 2.31), correlation and backward multiple regression techniques were applied on the following factors: T, T^2, ln(T), M_0, M_o^2, Ln(M_o), RH, RH^2, Ln (RH), V, V^2 and Ln (V). Misra and Brooker (1980) reported that parameters k and N can be expressed in terms of above factors by equations of the following form:

$$K=\exp[K_0+K_1T+K_2T^2+K_3Ln(T)\ \ldots\ K_{12}Ln(V)] \quad 4.6$$

$$N=N_0+N_1T+N_2T^2+N_3Ln(T)\ \ldots\ N_{12}Ln(V) \quad 4.7$$

where K_o, K_1 , K_2 ... K_{12} and N_0, N_1, N_2 ,...... N_{12} are constants, T is temperature in Kelvin, M_o is initial moisture content in decimal (db), RH, is relative humidity, decimal and V is air flow rate in m/s.

Correlation tests between K and above factors showed only T was significantly correlated to K, with correlation coefficients being well above 0.95 for all varieties. Backward multiple regression revealed that only temperature terms in Equation 4.6 were significant for naturally moist Brown, Red and White varieties. Hence Equation 4.6 reduced to the following form:

$$K=\exp[K_0+K_1T+K_2T^2+K_3Ln(T)] \quad \ldots \quad 4.8$$

A summary of constants in Equation 4.8 is given in Table 4.24

Table 4.24 Relationship between drying factors and parameter K for naturally moist grains

VARIETRY	K_0	K_1	K_2	K_3	R^2
WHITE	2865.1049	3.9411	-0.0029	-664.6705	0.9732
BROWN	1261.4288	1.8807	-0.0014	-297.6364	0.9709
RED	3887.1799	5.3759	-0.0040	-901.9886	0.9834

ANOVA carried out on these constants proved that the difference among the three varieties was insignificant, at 5% levels of significance. For rewetted sorghum, initial moisture content , air flow rate and relative humidity were also found to affect the value of K parameters . Hence for rewetted sorghum, Equation 4.6 took the following form:

$$K=\exp[K_0+K_1T+K_2T^2+K_3Ln(T)+K_4M_0+K_5V+K_6RH] \quad 4.9$$

Table 4.25 shows a summary of constants in Equation 4.9.

Table 4. 25 Relationship between drying factors and parameter K for rewetted grains

VARIETY	$-K_0$	$-K_T$	K_2	K_3	K_4	K_5	K_6	R^2
White-R	84.9077	0.0798	0.0001	17.7527	-0.0402	0.6584	5.2134	0.9682
Brown-R	3619.3930	4.8617	0.0036	833.9055	0.0374	-0.9885	2.3452	0.9932
Red-R	1713.1257	2.3838	0.0018	397.1063	0.0538	-1.3911	2.2132	0.9787

ANOVA based on these constants proved that the difference among rewetted varieties was also insignificant at 5% level of significance. Temperature terms, in an exponential form of Equation 4.7, were found to be adequate to express the relationship between parameters N and drying factors. Therefore, Equation 4.7 was modified to:

$$N=\exp[N_0+N_1T+N_2T^2+N_3Ln(T)] \quad \ldots\ldots \quad 4.10$$

A summary of constants in Equation 4.10 is given in Table 4.26.

Table 4. 26 Relationship between drying factors and parameter N

VARIETY	N_0	N_1	$-N_2$	$-N_3$	R^2
WHITE	7284.5779	10.2153	0.0077	1693.0682	0.8778
BROWN	2303.2570	3.2355	0.0024	535.4886	0.8083
RED	2340.1348	3.3296	0.0025	545.3636	0.8477
WHITE-R	2088.1027	2.8329	0.0021	482.3182	0.8667
BROWN-R	2084.5706	2.7610	0.0020	479.2727	0.8413
RED-R	442.5219	0.6081	0.0005	102.3636	0.8425

ANOVA carried out on these constants showed that here was no significant difference among varieties at 5% level of significance. The fact that different equations are necessary to express the relationship between parameters K and drying factors, for naturally moist and rewetted grains, is in line with published work by Misra and Brooker (1980) and Sokhansanj et al. (1984). Again, this can be explained by changes in grain characteristics such as density and bulk density during rewetting. Nevertheless, this contradicts the work reported earlier by Hustrulid (1962, 1963).

5. CONCLUSIONS

Based on the results of this study the following conclusions were made.

1. The EMC of grain sorghum is independent of variety. Sorption isotherms of grain sorghum are sigmoid in shape (BET type II) and exhibit hysteresis phenomenon. The hysteresis effects are maximum at 25°C but the span increases with increase in temperature, to cover the entire relative humidity range at 55°C and 70°C.

2. Sorption models tested had different fitting abilities to sorption data of grain sorghum. The GAB model was the best among models tested. The following simple empirical model was successful in predicting the sorption behaviour of grain sorghum for temperature and relative humidity conditions tested:

$$M = 0.3093 + 0.0307RH + 0.1588RH^2 - 8.2846 x 10^{-4}T$$

for desorption process and,

$$M = 0.3533 - 0.0305RH + 0.2061RH^2 - 9.3943 x 10^{-4}T$$

for adsorption process

3. The relationship between Parameter K in Pabis and Henderson equation (Equation 2.18) and drying air temperature is of Arrhenius type:

$$k = C_1 \exp\left(\frac{-C_2}{T}\right)$$

4. **Page equation (Equation 2.31) fitted drying data better than Pabis and Henderson equation (Equation 2.18). The relationship between Page equation parameters and drying factors is of the following form:**

$$K = \exp[K_0 + K_1T + k_2T^2 + k_3Ln(T)]$$

for naturally moist grains

$$K = \exp[K_0 + K_1T + K_2T^2 + K_3Ln(T) + K_4M_0 + K_5V + K_6RH]$$

for rewetted grains and

$$N = \exp[N_0 + N_1T + N_2T^2 + N_3Ln(T)]$$

for both naturally moist and rewetted grains.

6. SUGGESTIONS FOR FURTHER RESEARCH

From literature survey done during this study it was noted that information in some topics on grain sorghum is either lacking or inadequate. Based on this fact, and the results obtained from this work, further research is recommended in the following areas:

1. Sorption isotherms of sorghum flours.
2. Drying characteristics of sorghum grains subjected to repetitive wetting and drying cycles.
3. Diffusion models for predicting sorghum drying behaviour.
4. Further research on effect of relative humidity on drying rates of grain sorghum.
5. High temperature dehydration of sorghum grains. With the aim of acquiring useful information in production of puffed sorghum.
6. Equilibrium moisture characteristics of puffed sorghum.
7. The effects of drying temperatures on sorption properties of grain sorghum.

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8. APPENDICES

8.1 Appendix A :Chemical Composition of Grains

Table 8.1 Chemical composition of sorghum grains
(% by weight)

VARIETY	PROTEIN	STARCH	FAT	ASH	OTHERS
WHITE	7.36	69.33	3.24	1.83	18.24
BROWN	7.46	68.30	3.05	1.79	19.40
RED	7.43	68.77	3.16	1.67	18.97

The chemical composition of grains was done by the Goverment Chemist Department, Nairobi under the author's request.

8.2 APPENDIX B:DRYING DATA

Table 8.2 Drying Data at 40°C and V=0.9504 m/s.

Time(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	71.08	30.6	20.69	18.37	17.57	21.28
0.25	65.9	28.17	18.93	16.2	15.54	18.47
0.75	58.59	25.74	16.87	14.24	13.98	15.7
1.75	48.34	21.97	14.59	13.04	12.84	13.18
2.75	40.99	19.39	13.05	12.07	12.16	12.1
3.75	36.24	17.82	12.03	11.58	11.26	10.97
4.75	31.83	16.72	11.22	11.36	10.81	10.67
6.75	24.86	14.05	9.97	10.17	9.91	9.84
9.25	19.72	12.4	9.01	9.46	9.24	9.02
21.25	12.11	9.42	6.44	8.48	8.33	8.15
24.25	11.76	9.19	6.44	8.48	8.33	8.15
27.25	11.76	9.19	6.44	8.48	7.88	7.89
32.25	11.03	8.95	6.44	8.48	7.88	7.59
46.25	11.03	8.95	6.22	8.21	7.88	7.59
51.25	10.29	8.4	5.7	7.99	7.67	7.59
57.25	10.29	7.85	5.7	7.99	7.67	7.28

Table 8.3 Drying Data at 40°C and V=1.7781 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	52.41	14.09	25.79	14.45	17.77	21.74
0.5	47.59	13.28	23.12	12.98	15.12	18.17
1	43.35	12.48	20.68	12.15	13.8	15.04
2	35.95	11.54	18.25	11.33	12.1	12.83
3	28.87	10.55	16.07	10.71	10.59	11.47
4	24.35	10.11	13.88	9.87	9.64	10.11
6	18.11	9.57	12.66	9.87	9.26	9.91
8	14.44	9.16	10.71	9.23	8.7	9
22.75	8.49	8.18	7.79	7.99	7.38	7.69
26	7.65	7.55	7.3	7.56	7	7.44
30.5	7.65	7.37	7.3	7.36	7	6.99
49	7.08	6.97	6.82	7.36	7	6.99

Table 8.4 Drying Data at 50°C and V=0.9504 m/s

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	52.79	15.09	17.45	19	21.11	23.25
0.25	47	13.5	16.14	15.15	16.57	18.43
0.75	40.22	12.73	14.42	13.04	13.61	14.66
1.25	35.01	11.51	13.06	11.89	11.84	12.55
1.75	31.14	11.1	12.11	10.94	11.14	11.51
2.75	24.31	9.71	10.35	9.4	9.08	9.41
3.75	20.39	9.3	9.76	9.02	8.49	8.99
4.75	16.48	8.67	8.99	8.63	8.09	8.57
5.75	14.22	8.67	8.99	8.45	8.09	8.37
7.75	10.31	7.45	7.81	7.68	6.91	7.53
10.75	7.09	6.64	6.82	6.72	6.12	6.27
23	5.79	5.83	6.01	5.95	5.53	5.85
32	5.14	5.43	5.42	5.37	4.94	5.65
95.5	3.83	3.84	4.42	4.23	4.15	4.62

Table 8.5 Drying Data at 50°C and V=1.7781 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	56.41	17.88	16.94	21.4	22.06	23.73
0.25	52.44	15.46	15.49	17.12	17.3	19.19
0.75	44.21	13.48	13.65	14.41	13.85	15.09
1.25	38.11	12.59	12.64	12.65	12.18	12.93
1.75	33.24	11.5	11.81	11.68	10.97	11.42
2.75	25.31	10.17	10.6	10.51	9.72	10.19
3.75	20.73	9.62	10.19	9.34	8.89	9.3
4.75	16.16	8.39	9.39	8.37	7.87	8.43
5.75	13.41	8.16	8.76	7.78	7.23	7.79
7.75	10.37	7.51	8.35	7.4	6.81	7.36
10.75	8.54	6.62	7.53	6.62	5.98	6.72
23	6.71	5.29	6.1	5.45	4.73	5.61
27	6.71	5.29	6.1	5.45	4.73	5.4
32	6.71	5.29	6.1	5.45	4.73	5.4

Table 8.6 Drying Data at 60°C and V=0.9504 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	70.68	19.97	21.32	19.55	21.4	21.18
0.25	63.99	17.23	18.73	15.49	16.07	15.95
0.75	52.49	14.02	14.84	12.47	12.46	12.38
1.25	43.02	11.59	12.54	10.96	10.19	10.94
1.75	35.87	10.06	11.44	9.61	9.25	9.69
2.75	24.35	8.38	8.62	8.39	7.55	8.19
3.75	15.9	7.47	7.64	7.71	6.99	7.57
4.75	8.2	6.1	6.2	6.54	6.05	6.3
6.75	5.64	5.49	5.33	6.05	5.29	5.88
9.75	4.37	4.88	4.33	5.21	4.53	5.46
22.25	3.35	3.66	2.89	4.2	3.77	4.19
24.75	3.08	3.66	2.89	4.2	3.77	4.19
27.25	3.08	3.51	2.74	4.04	3.59	3.97
29.5	2.57	3.35	2.45	3.52	3.41	3.77

Table 8.7 Drying Data at 60°C and V=1.7781 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	65.99	30.47	31.47	22.83	22.63	23.84
0.25	59.74	25.95	28.57	17.41	16.53	17.75
0.75	48.91	20.77	22.79	14.06	13.19	13.16
1.25	38.36	16.09	17.93	11.03	10.63	10.45
2.25	24.19	10.73	11.72	8.85	7.88	7.52
3.25	16.17	9.23	9.75	7.84	7.88	7.52
4.25	11.35	8.36	8.23	6.95	7.09	7.11
5.25	8.82	7.35	7.48	6.42	6.5	6.49
7.42	7.18	6.34	6.11	5.7	5.91	5.87
9.67	6.26	5.52	5.2	4.97	5.32	5
22.92	4.66	3.86	3.67	3.88	4.14	4.19
26.42	3.95	3.5	3.06	3.19	3.74	3.35
39.42	3.95	3.5	3.06	3.03	3.74	3.35
46.75	3.95	2.85	2.61	3.03	3.15	2.93

Table 8.8 Drying Data at 70° C and V=0.9504 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	45.42	23.75	28.21	18.66	19.29	20.32
0.25	37.02	20.07	22.72	14.08	14.47	15.65
0.75	26.25	15.4	16.76	10.91	11.52	11.9
1.25	17.59	12.38	12.63	9.3	9.82	9.84
1.75	12.34	10.21	9.41	7.72	8.41	8.42
2.75	7.35	8.2	7.81	6.93	7.31	6.67
3.75	2.63	5.85	5.5	4.16	5.29	4.45
4.75	5.52	6.69	6.66	5.52	6.23	5.56
6.75	4.2	5.18	5.72	4.55	5.6	4.93
9.75	3.67	4.69	4.58	3.95	4.67	4.13
23.17	3.15	3.51	3.44	3.15	3.58	3.17
26.42	2.63	3.35	3.22	2.96	3.27	2.86
30.17	2.37	3.18	2.98	2.77	3.11	2.86

Table 8.9 Drying Data at 70°C and V=1.7781 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	53.4	23.89	30.27	18.79	19.71	21
0.25	46.06	19.59	25.11	14.14	13.83	15.14
0.75	32.63	13.41	17.33	9.88	9.47	9.45
1.25	22.83	10.65	13.1	9.1	8.71	8.53
1.75	15.49	8.93	10.13	7.75	7.69	7.37
3	7.07	6.36	7.36	6.19	7.42	7.2
4	5.87	6.02	6.82	5.62	5.9	5.52
5	5.64	5.5	6.08	5.22	5.13	5.03
6	4.65	5.16	5.54	4.84	4.88	4.61
8	4.16	4.3	4.79	4.25	4.61	4.18
10	3.67	3.96	4.43	4.06	4.61	3.76
23.75	2.69	2.58	2.94	2.51	3.08	2.6
31.5	2.19	2.41	2.94	2.12	2.56	1.83

Table 8.10 Drying Data at 80°C and V=0.9504 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	60.71	25.81	32.19	17.92	18.34	19.82
0.25	51.4	20.79	25.79	13.7	13.15	13.14
0.75	33.03	13.16	15.98	9.8	8.69	8.99
1.25	18.82	9.18	10.73	7.95	7.02	7.1
2.25	7.23	6.06	6.95	6.28	5.36	5.45
3.25	5.17	5.2	5.83	5.24	4.42	4.39
4.25	4.66	4.68	5.09	4.73	4.04	3.98
5.25	4.4	4.5	4.9	4.57	3.87	3.78
6.25	3.11	3.99	3.95	3.72	2.95	2.92
8.25	3.11	3.29	3.39	3.39	2.75	2.72
11	2.07	2.6	2.82	2.71	2.04	1.89
23.5	1.81	1.91	1.89	2.04	1.66	1.47
•28.75	1.81	1.91	1.69	1.87	1.49	1.27

Table 8.11 Drying Data at 80°C and V=1.7781 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	63.37	26.4	33.22	18.53	18.99	21.22
0.25	48.1	19.45	24.57	12.72	12.26	12.4
0.75	26.63	11.74	14.1	8.95	8.01	7.47
1.25	12.17	8.35	10.31	7.38	6.91	6.79
1.75	8.53	7.25	8.35	6.75	6.12	5.94
2.25	7.25	6.49	7.69	5.97	5.66	5.44
3.58	4.66	4.79	5.72	4.71	4.24	4.25
4.58	3.89	4.02	4.73	3.62	3.46	3.25
5.58	3.37	3.71	4.42	3.62	3.46	3.25
7.58	3.37	3.25	3.92	3.14	2.83	2.89
9.58	2.6	2.63	3.6	2.83	2.52	2.55
22.5	1.57	1.39	2.13	1.73	1.42	1.53
27.25	1.31	1.24	1.8	1.42	1.26	1.19

Table 8.12 Drying Data at 90°C and V=0.9504 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	69.81	29.96	34.77	18.7	21.12	23.51
0.25	49.86	19.23	22.49	11.29	11.51	12.6
0.75	18.36	9.52	11.45	6.85	7.02	7.9
1	14.17	8.71	10.45	6.47	6.84	7.34
1.5	8.4	6.69	7.89	5.55	5.69	6.01
2	6.3	5.27	6.49	4.44	4.69	5.08
2.5	5.51	4.66	5.51	4.07	4.11	4.7
3.5	4.46	4.05	4.92	3.32	3.73	4.33
4.5	3.94	3.44	4.32	2.96	3.33	3.77
5.5	3.41	3.24	3.92	2.41	2.94	3.39
6.5	3.41	3.24	3.74	2.41	2.94	3.02
8.5	2.63	2.63	3.15	2.04	2.54	2.64
• 10.5	2.36	2.23	2.78	1.49	1.97	2.26
23.5	0.79	0.61	1.19	0.57	0.37	1.13

Table 8.13 Drying Data at 90°C and V=1.7781 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	69.51	29.92	35.77	20.39	22.6	21.11
0.25	47.27	19.63	23.62	12.85	13.42	10.86
0.5	28.88	14.49	17.44	10.51	10.29	8.66
1	13.24	9.34	11.02	8	7.61	6.87
1.5	8.39	7.47	8.51	6.62	5.82	5.49
2	6.98	6.55	7.34	5.95	5.15	4.84
3	5.26	5.37	6.39	5.24	4.47	4.19
4	3.95	4.45	5.01	4.11	3.58	3.74
5	3.54	4.21	5.01	4.11	3.58	3.29
6	3.24	3.75	4.12	3.65	3.14	3.09
8	2.83	2.81	3.63	2.97	2.69	2.64
10	2.13	2.58	2.95	2.52	2.24	2.2
22.5	1.12	1.18	1.6	1.6	1.35	1.3

Table 8.14 Drying Data at 100°C and V=0.9504 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	29.7	27.07	29.82	16.35	18.25	18.55
0.25	14.25	15.86	16.98	9.85	9.52	9.4
0.75	5.03	8.05	8.22	6.24	5.82	6.16
1.25	3.64	5.61	5.91	4.81	4.24	4.7
1.75	2.82	4.64	4.88	4.09	3.97	3.84
2.83	2.25	3.66	3.85	3.37	3.18	3.25
3.83	2.25	3.42	3.6	3.12	3.18	3.25
4.83	1.39	2.19	2.31	1.68	1.85	1.79
6.83	0.57	0.98	1.29	0.96	0.79	1.19
9.83	0.57	0.98	1.29	0.96	0.79	1.19
16	0	0	0	0	0	0

Table 8.15 Drying Data at 100°C and V=1.7781 m/s.

TIME(t)	WHITE	BROWN	RED	WHITE-R	BROWN-R	RED-R
0	28.7	23.6	23.95	17.16	18.39	19.26
0.25	11.68	13.42	13.65	9.37	9.04	8.44
0.75	4.73	7.17	6.93	5.85	5.4	5.54
1.25	3.06	4.63	4.62	4.44	3.92	3.96
1.75	2.5	4.16	4.21	3.75	3.44	3.43
2.75	2.23	3.23	3.57	2.8	2.49	2.64
3.92	1.67	2.54	2.94	2.58	2.49	2.37
4.75	1.12	2.08	2.52	2.11	1.96	1.84
5.75	0.56	1.39	2.1	1.41	1.21	1.06
6.75	0.56	1.39	1.68	1.17	1.21	1.06
8.75	0.56	0.93	1.26	0.95	0.98	0.79
10.75	0.56	0.93	0.84	0.95	0.75	0.79
12	0	0.58	0.28	0	0	0
14	0	0.28	0	0	0	0
16	0	0	0	0	0	0