TWO-STAGE DRYING OF PADDY AND THE EFFECTS ON MILLED RICE QUALITY

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A Thesis submitted to the

Department of Agricultural Engineering

Kwame Nkrumah University of Science and Technology

in partial fulfilment of the requirements for the degree of

Master of Science (Food and Postharvest Engineering)

Faculty of Mechanical and Agricultural Engineering

College of Engineering

School of Graduate Studies

March, 2009

ABSTRACT

Two-stage drying of jasmine rice (*Oryza sativa* L.) cv *Khao Dawk Mali 105* and the effects on milling quality was studied. A laboratory fluidised bed dryer was used in the first stage to quickly reduce the initial moisture content of 22.44% wb to ≤19% wb. A second stage of drying using a static bed dryer and sun drying was further carried out until the final moisture content of ≤14% wb was achieved. The experimental drying temperatures at the fluidised bed drying stage were 60°C, 80°C and 100°C. The static bed dryer was adjusted to a tempering temperature of 45°C. The air flow rate at the first stage was set at 2.8 m/s and that of the second stage was 1.3 m/s. The bed depth of the samples at the fluidised dryer was 7cm while the initial mass of each sample was 370g.

The experimental data were fitted to the Page's and Single Exponential drying models to determine which would better describe the data. The Page's model gave a better description of the data (R^2 values as high as 0.966). Drying air temperature had the greatest effect on the rate of drying. Activation energy was calculated as 12.388×10^{-3} kJ/mol and 8.231×10^{-3} kJ/mol for fluidised and fixed bed and fluidised and sun drying respectively.

Head rice yield (HRY) of milled rice were 64.22%, 62.11% and 60.36% for fluidised bed drying at 60ºC (first stage drying) static bed drying at 45ºC (second stage drying) and subsequent storage for one, three and six months respectively. The samples dried at 80ºC and 45°C and subsequent storage for same months were 60.22%, 62.20% and 60.51%. Those dried at 100ºC and 45ºC were 59.54%, 62.37% and 57.35%. Complete sun drying had HRY of 62.27%, 63.55% and 61.91%. Those samples which were dried with the fluidised bed dryer and subsequently sun dried and stored for only one month had HRY of 63.29%, 60.06%, 58.37% and 64.25% for drying at 60ºC, 80ºC 100ºC and complete sun drying respectively.

It was concluded that drying at 60ºC and storing for one month gave the best HRY for the laboratory dryers whilst complete sun drying had the best HRY at one month storage, though it took an extended time.

Head rice yields for the mean drying temperatures and duration of storage were compared; there was no significant difference ($p > 0.05$) between the mean temperatures and months of storage of dried paddy.

DECLARATION

I hereby declare that this submission is my own work towards the award of Master of Science (Food and Postharvest Engineering) and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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AKNOWLEDGEMENTS

My topmost appreciation goes to my first supervisor, Dr. Ahmad Addo, for supervising this work and for his continual guidance and encouragement during my study period. I deeply acknowledge his patience in reading, constructive criticisms and for correcting this manuscript.

I would like to extend my special thanks to my second supervisor, Dr. J. O. Darko, for his valuable advice and encouragement during the course of my study and also for reading through the manuscript and correcting my mistakes.

My heartfelt gratitude also goes to my lecturers, friends and the staff of the Agricultural Engineering Department of the Faculty of Mechanical and Agricultural Engineering, College of Engineering, Kwame Nkrumah University of Science and Technology for their valuable teaching, encouragement and assistance.

I wish to also extend my appreciation to Mr. Barns-Akutey Akpene of the Ghana Irrigation Development Authority (GIDA), Ashaiman, Greater Accra, for his assistance during the milling phase of my research. My thanks also extend to Bernard Baiden and Kofi Debrah, who were undergraduate students for their assistance during my research. Thank you all.

Finally, my sincerest thanks go to my Wife (Issahaku Rahma Pumaaya) for her support, prayers and encouragement, my late father and mother (Mr. Dokurugu Tampuli and

Miss Tasalla Ziblim) and the entire family for nurturing me. I also thank all my siblings and friends for their support, prayers and encouragement.

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NOMENCLATURE

Symbol

HRY	Head Rice Yield (%)
GIDA	Ghana Irrigation Development Authority
MC wb	Moisture Content, Wet Basis (%)
MC db	Moisture Content, Dry Basis (%)
wb	Wet Basis
db	Dry Basis
k	Drying constant (H^{-1})
n	Drying constant (-)
a	Drying constant (-)
R^2	Coefficient of Determination
RME	Root Mean Error
RMSE	Root Mean Square Error
M	Moisture Content (%)
M_0	Initial Moisture Content (%)
M_i	Moisture Content at i^{th} time (%)
EMC	Equilibrium Moisture Content (%)
IMC	Initial Moisture Content (%)
RH	Relative Humidity
U	Air velocity
U_0	Air velocity for incipient fluidisation
MR	Moisture Ratio

t	Time (h)
ASAE	American Society of Agricultural Engineers
W_0	Initial weight of sample (g)
W_i	Weight of sample at ith time (g)
KNUST	Kwame Nkrumah University of Science and Technology
N	Number of observations
T	Absolute temperature (K)
R	Universal gas constant (0.008314 kJ/mol/K)
E	Activation Energy (kJ/mol)
k_0	Frequency factor (h^{-1})
Σ	Summation

CHAPTER ONE

INTRODUCTION

1.1 Background information

Harvested paddy grain (rice) is usually of high moisture content. One of the most important factors in maintaining the quality of paddy is its moisture content which must be in the suitable range (≈14% wet basis or less) for long term storage and quality milling. High moisture leads to deterioration in seed quality as a result of micro-organism growth and respiration. In contrast, too low moisture can lead to unnecessary energy consumption and cracked seeds during drying and milling. Therefore it is necessary to bring the moisture content of paddy to 14% wb or less for safe storage and processing.

Rice is one of the major staple crops in Ghana. The demand for rice in the West African sub region is growing faster than any other major source of calories for especially urban dwellers. Local production and processing usually yields rice of poor quality for storage and consumption. This is due to inadequate knowledge of processing, especially with the control of moisture content. According to Ahmed *et al.* (2006), moisture content is one of the most important factors affecting the quality of rough rice during storage and that, it is at a high level at the time of harvest and must be reduced to nearly 14% wb with an appropriate drying process.

1.1.1 Seed drying problems

Paddy grain is different from other grains because it has an outer husk cover and a bran layer. Therefore, the heat and mass transfer processes occurring in paddy grain drying are different from other cereal grains (Bunyawanichakul *et al.*, 2007)

Rice kernel fissuring can occur in the field prior to harvest, or during harvesting, processing and storage. Experimental results (Aguerre *et al.*, 1986; Bonazzi *et al.*, 1997) have shown the relationship between the drying conditions and the percentage of broken kernels measured after milling, which takes place after the drying step. Contrary to other cereals, rice is preferably consumed as whole grains. An important quality criterion for rice is the percentage of whole, unbroken rice kernel. The economic value, according to Siebenmorgen (1994), of the dried product is strongly dependent on the percentage of unbroken kernels, which are roughly twice as much as broken kernels.

Owing to the high moisture content of the harvested paddy and unfavourable weather conditions, especially during the wet season, paddy drying is usually carried out in two steps to give acceptable results (Tumambing, 1986).

1.1.2 Two–stage drying concept

Using two-stage drying, high moisture paddy is rapidly reduced to a more manageable level (around 18-19% wb) using fast rate drying (Bunyawanichakul *et al.*, 2007). This is an appropriate final moisture content for fast rate drying because the percentage of head rice yield decreases significantly when the final moisture is lower than 18-19% wb (Sutherland and Ghaly, 1990).

At 18-19% wb moisture content, paddy can be kept for up to three weeks without excessive deterioration in quality (Discroll and Adanezak, 1987). During that period, the moisture content of paddy can be reduced to 14% wb using a slow rate dryer.

1.1.3 Dryers for two-stage drying systems

Normally, two-stage drying systems require specific types of dryers for each stage. The first stage requires a dryer that has a high drying rate such as a fluidised bed. Safe storage requires rapid decrease in moisture to preserve quality (Soponronnarit *et al.*, 2000). Fluidised bed drying is recognised as a fast drying technology, due to the large air to product contact area achieved relative to a static bed caused by fluidisation of the product, and the high air speed and high temperatures used. Dryers that use a low air temperature and low air velocity (such as in-store dryers) are normally selected for the second stage of drying.

Some researchers, including Soponronnarit (1990), have developed commercial continuous flow dryers in the past for fast rate drying. Such type of commercial dryers needs to be introduced in Ghana, especially southern Ghana, where harvesting of rice is done in the rainy season. During such periods, drying is almost impossible because of the high moisture content at harvest, which is not suitable for open air drying. When the harvested grains are left on the field for a few days without drying, deterioration in the form of mould, heat, discolouration and others set in. The farmer and the nation would be at the losing end. Laboratory drying of paddy has already been done at the KNUST, Department of Agricultural Engineering (Minkah, 2006). This study is to test the suitability of using fluidised bed drying to immediately reduce the moisture content of paddy harvested in Southern Ghana to a safe storage level, so that sun drying or slow rate dryers would be used in the second stage of drying, when the weather conditions are favourable.

1.1 Hypotheses

According to this background information, the following hypotheses were proposed for this research:

- Two-stage drying is an efficient and effective method for drying of paddy.
- Sun drying creates lesser cracking in paddy than heated air drying.

1.3 Scope of Work

The two-stage drying technique studied in this research used a laboratory scale batch fluidised bed dryer in the first stage and a fixed-bed dryer, as an in-store dryer, in the second stage. The rice variety adopted for this research was the jasmine variety, grown and harvested in Ghana.

Drying experiments were conducted using the batch fluidised bed dryer to dry the rice samples from a moisture content of about 23% wb to ≤18% wb, at air temperatures between 60-100°C. The fixed bed dryer (set to 45°C) was initially used and then sun drying was used to continue the drying process from about 18% wb to approximately 14% wb. The details of the experiments are described in Chapter Three.

The second part of the experiments involved storage of the samples for a maximum of six months. Milling experiments were then carried out and the quality of the milled rice determined.

1.3.1 General Objective

The main objective of this study was to carry out a two-stage drying of jasmine rice using a fluidised bed for the first stage and a fixed bed or sun drying for the second stage and determine their effects on milling quality.

1.3.2 Specific Objectives

The specific objectives were to evaluate the effects of two-stage drying on:

1. drying characteristics of jasmine rice samples and
2. milling properties of jasmine rice.

CHAPTER TWO

LITERATURE REVIEW

2.1 Principles of grain drying

Grain drying is the phase of the post harvest system during which the product is rapidly dried until it reaches a 'safe moisture' level (de Lucia and Assenato, 1994). It is achieved by the evaporation of moisture from the grain. Therefore, drying involves both heat and mass transfer operations simultaneously (Chakraverty, 1994). In convective drying, the heat required for evaporating moisture from the drying product is supplied by the external medium, which is usually air.

The drying process involves two basic mechanisms; the migration of moisture from the interior of an individual grain to the surface and the evaporation of moisture from the surface to the surrounding air (Trim and Robinson, 1994). Grain drying can be achieved by circulating air at varying degrees of heat through a mass of grain (de Lucia and Assennato, 1994). As it moves, the air imparts heat to the grain, while absorbing the humidity of the outermost layer. However, this process does not take place uniformly inside the drying chamber or among individual grains, or within each grain. Indeed, the water present in the outer layers of the grain evaporates much faster and more easily than that of the internal layer. This implies that it is much easier to lower the moisture content of the grain from 35% to 25% than from 25% to 15%. Trim and Robinson (1994) stated that drying operation must not be considered as merely the removal of moisture since there are many quality factors that can be adversely affected by incorrect selection of drying conditions and equipment. It is therefore important to understand the principles of grain drying (whether it is being dried by natural or artificial drying system) to ensure that a high quality product is obtained.

2.1.1 Grain equilibrium moisture content

The concept of equilibrium moisture content (EMC) is important in the study of grain drying because it determines the minimum moisture content to which grain can be dried under a given set of drying conditions (Brooker *et al.*, 1992). As a result, the EMC of a grain as defined by Brooker *et al.* (1992) is the moisture content of a material after it has been exposed to a particular environment for an infinitely long period of time. Alternatively, they defined EMC as the moisture content at which the internal product vapour pressure is in equilibrium with the vapour pressure of the environment.

The EMC is useful in determining whether a product will gain or lose moisture under a given set of temperature and relative humidity conditions. Thus, EMC is directly related to drying and storage (Chakraverty, 1994). Different materials have different equilibrium moisture contents. It is dependent upon the temperature and relative humidity (RH) of the environment and on the variety and maturity of the grain. Specific values of EMC are tabulated in Table 2.1.

Table 2.1 Equilibrium moisture content of grains (% wet basis)

Grain	Temperature (°C)	Relative humidity (%)									
		10	20	30	40	50	60	70	80	90	100
Rice, milled	25	4.9	7.7	9.5	10.3	11.0	12.0	13.4	15.3	18.3	23.3
Rice, rough	25	4.6	6.5	7.9	9.4	10.8	12.2	13.4	14.8	16.7	25.7

Source: Brooker *et al.*, 1992.

It can be seen from the table that the EMC of grains increases as the RH of the air increases. For instance, a moisture content of 16.7% for rough rice can only be attained when it is exposed to air at 25°C and 90% RH. Similarly, to dry rough rice to moisture content lower than 16.7% requires air temperature increased or its humidity reduced.

A variety of methods have been employed for determining the EMC values of cereal grains. Most of the available data have been obtained by exposing a grain sample to water in a moist-air environment. Brooker *et al.* (1992) have grouped EMC determination methods into two; the techniques are either static or dynamic. In the static method, a grain sample is allowed to come to equilibrium in still, moist air. In the dynamic method, the air is mechanically moved. The static method requires several weeks before equilibrium is reached. At high humidity and temperature, the grain may mould before equilibrium is attained. The dynamic method is quicker and thus, preferred (Brooker *et al.*, 1992).

2.1.2 Drying rate

In drying high-moisture rough rice with heated air, drying starts from the surface of the kernel and progresses inward (Abe *et al.*, 1992). They stated in their study that drying too rapidly causes "case hardening" whereby the surface of the grain dries out rapidly sealing the moisture within the inner layers. The internal pressure thus developed causes cracks to develop. They concluded that the same phenomenon accounts for the development of chalky grains.

Drying rate generally increases with increasing moisture content of grain and air temperature or decreases with increase in air humidity (Trim and Robinson, 1994). Chakraverty (1994) generalises the factors that affect drying rate as temperature, air flow rate, relative humidity, exposure time, types, variety and size of grain, initial moisture content, grain depth etc. However, Henderson and Pabis (1961) found out that air rate had no observable effect on thin layer drying of wheat when air flow was turbulent. According to them, air flow rate varying from $10cm^3/sec/cm^2$ to $68cm^3/sec/cm^2$ had no significant effect on the drying rate of wheat. A similar observation was also made by Hustrulid (1962, 1963), when he found out that wheat did not show any change in drying rate after rewetting. Thin-layer drying rates of sunflower seed were determined by Syarief *et al.* (1984) over a temperature range of 27°C-93°C, initial moisture contents of 21-26%, drying air velocity of $0.1\text{-}0.5m^2/s{\bullet}m^2$, and 20-80% relative humidity. Drying air temperature was found to have the greatest effect on drying rate followed by air velocity and initial moisture content. Relative humidity had the least effect of all and was not included in their model development.

According to Pathak *et al.* (1991), Syarief *et al.* (1984) evaluated several empirical and semi-empirical thin-layer drying equations and found out Page's equation to best describe the data. Model parameters were statistically obtained to be functions of temperature alone. Li *et al.* (1987) confirmed the Syarief's model based on Page's equation and extended it by including initial moisture content as a parameter to cover the initial moisture range up to 33% db.

The drying rate for the single exponential equation can be directly computed from equation 2.1.

$$\frac{dM}{dt} = -k(M - M_e) \qquad (2.1)$$

where:

$\frac{dM}{dt}$ = drying rate

k = drying constant (h^{-1})

M = initial moisture content (% dry basis (db))

M_e = equilibrium moisture content (EMC) (% dry basis (db))

Equation (2.1) considers the resistance to the drying concentrated on the grain surface and adjusts the drying rate curve by a straight line. Drying rate generally increases with increasing moisture content of grain and air temperature decreases with increase in air humidity, but it is independent of air flow rate when air velocity exceeds 0.25 m/s by a decrease in equilibrium moisture content.

The equation suggests that during the falling drying rate period of porous hygroscopic materials, the drying rate (rate of change of moisture content) is proportional to the instantaneous difference between the material moisture content and the expected material moisture content when it is in equilibrium with the drying air. It is assumed that the material layer is thin enough and the air velocity is high, so that the conditions of the drying air (humidity, temperature) are constant throughout the material (Karathanos and Belessiotis, 1999). The solution of equation 2.1 results in equation 2.2.

2.2 Options for grain drying

In this section are summarised results of published studies on possible options of drying of grains. They include thin layer drying, high temperature drying and two-stage drying.

2.2.1 Thin layer drying of rice

Thin layer drying refers to the grain drying process in which all grains are fully exposed to the drying air under constant drying condition, i.e., at constant air temperature and humidity (Chakraverty, 1994). Generally, a recommended air-grain ratio is taken as thin layer.

The process of drying is approached from two points of view: the equilibrium relationship and the drying rate relationship. Equilibrium moisture content is reached when the grain is exposed to a continual supply of air at constant temperature and humidity, having a fixed partial pressure of the vapour, p. The grain will either lose moisture by evaporation or gain moisture from the air until the vapour pressure of the moisture of the grain equals p (Chakraverty, 1994). The drying rate relationship consists of the constant rate period and the falling rate period.

Some crops including cereal grains at high MC are dried under constant-rate period at the initial period of drying. Falling-rate period follows subsequently. Wheat for example according to Chakraverty (1994), is dried under constant-rate period when its MC exceeds 72%. In the constant-rate period, the rate of evaporation under any given set of air conditions is independent of the solid (grain) and is essentially the same as the surface under the same condition. Chakraverty (1994) listed some factors on which the rate of drying in the constant-rate period depended upon. They include:

a) difference (in humidity) between the temperature of air and temperature of the wetted surface at constant air velocity and RH,
b) difference (in humidity) between air stream and wet surface at constant air velocity and temperature and
c) air velocity at constant air, temperature and humidity.

Cereal grains are usually dried entirely under falling-rate period. The falling-rate period enters after the constant drying rate period and corresponds to the drying cycle where all surface is no longer wetted and the wetted surface conditionally decreases, until at the end of this period, the surface is dry. Chakraverty (1994) ascribes the cause of falling off in the rate of drying to the inability of the moisture to be conveyed from the centre of the body to the surface at a rate comparable with the moisture evaporation from its surface to the surroundings.

The falling-rate period is characterised by increasing temperature both at the surface and within the solid. Furthermore, changes in air velocity have a much smaller effect than during the constant rate period. The falling-rate period of drying is controlled largely by the product and is dependent upon the movement of moisture within the material from the centre to the surface by liquid diffusion and the removal of moisture from the surface of the product (Chakraverty, 1994).

2.2.3 High temperature drying of paddy

Hot air drying is the most common method used for food dehydration. The quality of a food product is sensitive to the drying temperature (Luangmalawat *et al.,* 2007). The temperature may cause the degradation of food qualities, such as colour, shrinkage, nutritional substances, dehydration capability and microstructure (Aguilera, 2005; Attanasio *et al.*, 2004; Bello *et al.*, 2006; Silva and Avila, 1999; Thipayarat and Leelayuthsoontorn, 2006). All these physical and chemical changes have an influence on consumer acceptability. When heated air is used to dry high moisture paddy, drying of the paddy usually starts from the surface of the kernel and progresses inward. Drying too rapidly causes "case hardening". This happens when the surface of the grain dries out rapidly sealing the moisture within the inner layers. The internal pressure thus developed causes cracks on the grain (Abe *et al.,* 1992). They explained further that the same phenomenon accounts for the development of chalky grains. Grains which are cracked result in the breakage of rice during milling. This leads to a reduction in milling recovery, both quantitatively and qualitatively (Abe, *et al.,* 1992).

A two-stage paddy drying carried out by Messo *et al.* (2004) suggested that high temperature used in the first stage led to the development of a moisture gradient inside each grain kernel and resulted in cracking and breakage of the paddy kernels. This problem, they suggest can be solved by introducing a tempering process between the two stages in order to increase or maintain the two stages so as to increase or maintain the paddy head rice yield and reduce the paddy moisture content in the second stage (Soponronnarit *et al.*, 1999; Steffe *et al.*, 1979).

Bunyawanichakul *et al.* (2007) in their work on modelling paddy grain drying in a simple pneumatic dryer established that the whiteness of milled rice decreases with an increasing grain temperature, drying temperature and exposure time. Chemical and physical transformations induced by heating (Maillard reaction) and translocation of colour from rice husk and bran to endosperm cause discolouration. Longer drying time and higher moisture content during heating also accelerate the Maillard reation, but do not affect the rate of water removal.

Changes that result from the functionality associated with the temperature and time used in drying have been reported in several publications. Yamashita (1996) demonstrated that when drying temperature exceeded 40°C, rice taste quality decreases. Meullenet and Mauromoustakos (1998) observed that a high temperature (54.3°C) resulted in softer cooked rice kernels but higher cohesiveness based on texture profile analyser. David and Webb (1971) reported that drying at elevated temperatures (up to 71°C) caused neither marked improvement nor deterioration in the cooking quality of milled rice. Zheng and Lan (2007) found out that taste of rice increases with the increase of initial paddy moisture content at the same drying temperature. The taste begins to drop for paddy with relatively high initial moisture content (IMC) at low drying temperature. For paddy with IMC of 25%, they found that, the taste significantly decreases at drying temperatures above 35°C.

2.2.4 Two-stage drying of paddy

Paddy is usually harvested at high moisture content levels, ranging 25-40% db (Atthajariyakul and Leephakpreeda 2005). Such a high moisture paddy when stored before milling will cause the development of high temperature at storage, serious discoloration and odours and ultimately reduced milling yield due to the growth of moulds and other microorganisms (Araullo *et al.*, 1987). The grain must be dried to a moisture content of 14% wb to ensure long storage life and high milling quality (Kunze and Calderwood, 1980). Owing to the high moisture content of the harvested paddy and unfavourable weather conditions, especially during the wet season, paddy drying is usually carried out in two stages with acceptable results (Tumambing, 1986).

Srzednicki and Driscol (1995) in presenting a paper on "In-store Drying and Quality Maintenance in Grain", pointed out that a two-stage drying or combination-drying strategy could be a suitable way to solve the dilemma of fast drying and quality grains. Two-stage paddy drying; fast dried in a fluidised dryer and then slowly dried by in-store drying to moisture contents of 23% dry basis (db) and 16% db respectively, was recommended by Soponronnarit (1995) to maintain paddy qualities, such as head rice yield and whiteness. This suggestion was also supported by Ng *et al.* (2005).

Recently, various researchers have shown that paddy dried by a high-temperature, fast rate fluidised bed drying technique (140-150°C) has high head rice yield (Soponronnarit and Prachyawarakorn, 1994; Taweerattanapanish *et al.*, 1999). The technique has thus become an increasingly more popular technique for paddy drying. High temperature used in their study (during the first stage of drying) led to the development of a moisture gradient inside each grain kernel and resulted in cracking and breakage of the paddy kernels. Soponronnarit *et al.* (1999) and Steffe *et al.* (1979) suggested that the problem could be solved by the introduction of a tempering process between the two stages (first and second stages of drying) in order to increase or maintain the paddy head rice yield and paddy moisture content in the second stage. Using two-stage drying, the high moisture content is rapidly reduced to a manageable level (around 18-19% wb) using fast rate dying. This is appropriate final moisture content for fast rate drying because the percentage of head rice yield decreases significantly when the final MC is lower than 18-19% (Sutherland and Ghaly, 1990).

Commercial fluidised bed paddy dryers have been successfully developed using the principle of two-stage drying (Soponronnarit *et al.*, 1995). These are with conveying systems and are usually associated with bulk handling and storage systems that make them appropriate for cooperatives and commercial millers. For the individual farmer, immediate threshing and drying of wet harvested paddy to 18-19% wb is a practical method to arrest deterioration and increase selling price (Bunyawanichakul *et al.*, 2007). They suggested that, a suitable dryer for this purpose is a compact mobile unit that uses high temperature heating and has a very short grain exposure and grain residence time. According to them, they (the compact mobile units) would be attractive to individual farmers, if they are operated on a custom basis as for the mobile paddy thresher and combine harvester.

Soponronnarit (1999) contended that, Sutherland and Ghaly (1990) were probably the first research group who investigated the feasibility of using fluidisation technique for paddy drying. Experimental results showed that head yield was 58-61% when paddy was dried from 28.2 to 20.5% db but was 15-24% when the final moisture was 19% db.

Tumambing and Driscoll (1993) found that drying rate was affected by drying air temperature and bed thickness under experimental conditions as follows:

- drying air temperature of 40-100°C,
- bed thickness of 5-20 cm and
- air velocity of 1.5-2.5 m/s.

Sutherland (1984) in his concluding remarks on the design methods for fixed-bed and fluidised bed driers for paddy rice, said it was applicable to use these two driers in all countries as artificial driers for paddy, both on individual farms and at receiver depots.

A fluidised-bed dryer differs from a fixed-bed dryer only with respect to the velocity of the drying air (figure 2.1 A and B).

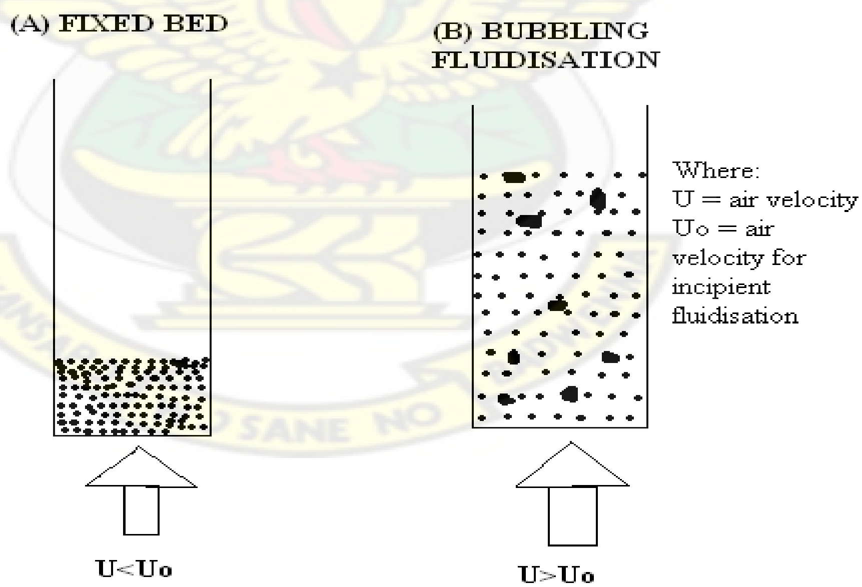

Figure 2.1: Schematics of fixed bed and fluidised bed grain dryers
Source: Brooker *et al.*, 1992

The kernels in a fixed bed dryer remain in place due to the relatively low flow rate of the air. They are suspended in air in a fluidised bed dryer (Brooker *et al.*, 1992). They explained that, as the velocity of the air of a grain bed increases, the static pressure of the drying air also increases until it reaches the equivalent of the weight of the kernels per unit area of bed, and the kernels become suspended or fluidised in the air. Moderate mixing of the kernels results during the fluidisation process. As the air velocity is further increased, air bubbles form within the bed, resulting in vigorous mixing of the kernels. According to Brooker *et al.* (1992) fluidised drying of grain functions best at air velocities slightly above the fluidisation velocity (U_o). They advised that, excessive bubble formation should be prevented because it results in inefficient use of fuel and of electric power.

Brooker *et al.* (1992) listed some advantages of a fluidised bed grain dryer over other types as:

i. Rapid mixing of the kernels, resulting in nearly homogeneous drying of the grain, thus permitting reliable control of the maximum grain temperature and
ii. High heat and mass transfer rates between the air and the kernels due to the high air velocity.

They also outlined a number of disadvantages of a fluidised bed as:

i. High electric power requirements because of the high air velocity,
ii. High specific energy consumption due to the low RH of the exhaust air,

iii. Dusty environment around the dryer if no air pollution requirement (i.e., a cyclone or bag filter) is employed (assuming the pressure in the dryer is higher than that of the ambient air),
iv. Limited allowable size distribution of the kernels and
v. Inability to dry very moist sticky kernels (e.g. parboiled rice).

2.3.1 Effects of drying on milling of paddy

By definition, the milling yield of paddy is an estimate of the quality of whole kernels and total milled rice (whole and broken kernels combined) that are produced in the milling of rough rice to a well milled degree (Webb and Stermer, 1972). Previous experimental results (Aguerre *et al.*, 1986; Bonazzi *et al.*, 1997) have shown the relationship between the drying conditions and the percentage of broken kernels measured after milling, which takes place after the drying step. Drying and also harvesting and storage induce cracks in the grains, leading to breakage during milling (Kamst *et al.*, 1999). Contrary to other cereals, rice is preferably consumed as whole grains. An important quality criterion for the rice industry is therefore the percentage of whole, unbroken rice kernels. The economic value of the dried product is strongly dependent on the percentage of unbroken kernels, which are strongly worth twice as much as broken kernels (Siebenmorgen, 1994). As the cooking quality of broken rice is very poor, the market price with broken grains is much less than that for whole grains (Li *et al*., 1999). The ultimate goal of the rice industry is to achieve maximum head rice yield from the milling process. According to Iguaz *et al*. (2006) HRY is the current standard to assess commercial rice milling quality.

Abe *et al.* (1992) concluded that drying parameters affected the quality of dried grain. They explained that, drying air temperature range of 45°C to 50°C, air flow rate of 0.3 m^3/min•kg to 0.5 m^3/min•kg, exposure time of 5 min to 10 min, tempering temperature of 25°C and tempering time of 50 min is considered most appropriate for obtaining good quality and tasty rice. Abe *et al.* (1992) further advised that, drying operations should not be concentrated on physical phenomena like cracking only. However, chemical phenomena such as breakdown of some lipids and sugar during drying operation require understanding and control.

Stress cracks are fine fissures in kernel endosperm. In general, the formation of stress cracks is associated with rapid drying of the rough rice. The development of stress cracks is proportional to the magnitude of the temperature and moisture gradient set up when heat is applied to moist grains (Abe *et al.*, 1992). Cracked grains, according to Abe *et al.* (1992), contributed to breakage of rice grains during milling and hence results in reduction of milling recovery quantitatively and qualitatively. In their experiment on effects of drying parameters on quality of artificially dried rough rice, Abe *et al.* (1992), observed that, tempering temperature in the tempering tank (stage) when lowered to about 25°C would not only reduce the ratio of cracked grains but would also result in dried grains of much better quality. They also found that, rice grain lower in viscosity and rice high in protein produced cooked rice that is less sticky. Rice of high moisture content, 16% wb produces cooked rice that is softer and stickier. The higher the free fatty acid content, the less favourable the taste of the cooked rice becomes, they established.

Although the moisture gradient was not measured in the experiments of Kunze (1979), it was believed that the reclining gradient after rapid drying is the cause of fissures which develop. Length of drying time and span of moisture through which the grains were dried, showed little relation to the number of fissured grains which were observed immediately after drying. Damage, subsequent to drying of high moisture grains, was dependent on how fast the samples were dried for a period of one hour or more. Rapidly dried high moisture rice can be milled immediately after drying to give a head rice yield. The rice will then fissure in the milled condition (Kunze, 1979).

High drying temperatures alone are not sufficient to cause cracking (Bonazzi *et al.*, 1997). Two main causes of cracking as characterised by Kunze (1979) were adsorption and desorption of moisture. When temperature gradient is combined with moisture gradient, the stresses are detrimental enough to produce cracking in grain kernels (Ng *et al.*, 2005). A high temperature and low humidity surrounding caused rapid evaporating capacity and increased the moisture gradient in the kernel. Therefore, Bonazzi *et al.* (1997) suggested using heated air with high relative humidity in drying, which produced low cracking and good head yield and also halfed the operation time.

Fissuring can occur in the field prior to harvest, or during harvesting, processing and storage. Improper drying and tempering processes can be a major cause of fissuring (Ban, 1999; Kunze and Choudhury, 1972; Kunze, 1979; Sharma and Kunze, 1982; Nguyen and Kunze, 1984; Bautista, *et al.*, 2000; Cnossen and Siebenmorgen, 2000). Understanding the effects of drying and tempering processes on rice kernel fissuring is important to control and optimize drying and tempering conditions for maximising milling quality (Cnossen *et al.*, 2002).

2.4 Drying models

A number of researchers have proposed various simplified models for explaining the drying behaviour of their products. A semi-empirical relationship, the so-called "thin layer" equation that is analogous to Newton's law of cooling was introduced for explaining the drying rate of food grains (Soponronnarit, 1997).

Thus thin-layer drying refers to the drying of grain fully exposed to the ventilating air causing all grains to dry uniformly throughout the drying layer (Meas, 1999). Thin-layer drying modelling contributes to the understanding of the drying characteristics of agricultural materials (Lahsasni *et al.*, 2003). They have categorised thin-layer drying models into three categories, namely theoretical, semi-theoretical, and empirical. The theoretical approach concerns either the diffusion equation of simultaneous heat or mass transfer equations. The empirical equations are easily applied to drying simulation as they depend on experimental data (Table 2.2). Among these models, the theoretical approaches take into account only the internal resistance to moisture transfer while the semi-theoretical and empirical approaches consider only the external resistance to moisture transfer between the product and air (Mujumdar, 1987; Jayas *et al.*, 1991; Hassan and Hobani 2000; Basunia and Abe 2001, Yaldiz and Ertekin 2001 a; Yaldiz *et al.*, 2001 b; Midilli and Kucuk 2003; Lahsasni *et al.*, 2004 a, 2004 b).

Table 2.2 Mathematical models usually applied to drying curves

Model name	**Model Expression**
Newton (Exponential)	MR = exp(-kt)
Page	**MR = exp (-kt^n)**
Modified Page	MR = exp (-(kt)^n)
Single exponential (Henderson and Pabis)	MR = a exp (-kt)
Logarithmic	MR = a exp (-kt) + c
Two term	MR = a exp (-k$_0$t) + b exp (-k$_1$t)
Two-term exponential	MR = a exp (-kt) + (1-a) exp (-kat)
Wang and Singh	MR = 1 + at + bt^2

Source: (Lahsasni *et al.*, 2003).

The most commonly used thin layer drying models are described below:

a) The Newton (or exponential model)

This is a lumped model analogous to Newton's Law of cooling in heat transfer and is used often to describe mass transfer in thin-layer grain drying (equation 2.2).

$MR = \exp(-kt)$..(2.2).

where;

MR = moisture ratio (dimensionless)

k = drying constant (h^{-1})

t = drying time (h)

This equation (2.2) has been employed by several researchers (Ross and White, 1972; Westerman *et al.*, 1973 and Hukill and Schmidt, 1960 and Ghaly and Sutherland, 1984). Usually, this model does not provide an accurate simulation of drying curves of many food products, underestimating the beginning of the drying curve and over-estimating the later stages (Sogi *et al.*, 2003).

b) Page's model

This is an empirical modification of the exponential model (equation 2.2).

$MR = \exp(-kt^n)$...(2.3) .

where:

MR, k and t remain as defined previously.

n = drying constant.

Equation 2.3, developed by Page (1949), is usually applied to overcome the shortcomings of the exponential model and is applied with an empirical modification to the time term by introducing an exponent '*n*' (Akpinar *et al.*, 2003; Iguaz *et al.*, 2003). The form of Page's equation has been successfully employed for several grains by several researchers (Agrawal and Singh, 1977, 1984; Li and Morey, 1984; Wang and Singh, 1978). This model has been used to accurately simulate the drying curves of rough rice (Iguaz *et al.*, 2003), potato slices (Akpinar *et al.*, 2003), green bean, potato and pea (Senadeera *et al.*, 2003), carrot (Doymaz, 2004; Misra and Brooker, 1980; Ross and White, 1972; White *et al.*, 1973) among others.

Li and Morey (1984) dried 150 g sample yellow dent maize in wire-mesh tray of 17.8 × 17.8 at 27, 49, 71, 93 and 116°C. The authors used Page model to fit the experimental data while the time (t) was expressed in minute. The purpose of the experiment was to determine the thin-layer drying rates (as affected by drying air temperature, air flow rate, initial MC and RH) and to develop an equation that fits the data and is suitable for use in a deep-bed drying model.

The drying constants, *k* and *n*, for each drying temperature were determined using linear regression on the transformed equation.

$$\ln(-\ln MR) = \ln k + n(\ln t) \quad (2.4)$$

c) Modified Page model

The modified form of Page's equation has been used by a number of researchers to describe their experimental data.

$$MR = \exp\left(-(kt)^n\right) \quad (2.5)$$

Overhults *et al.* (1973) studied the thin-layer drying characteristics of soybeans with initial moisture content ranging from 20% to 33% and drying air temperatures from 38°C to 140°C. Dew point temperature was held constant at 8°C. Equation 2.5 was employed to describe the experimental data.

Other investigators (White *et al.*, 1973; Flood *et al.*, 1972; and Wang and Singh, 1978) have also utilised the modified Page equation to predict the fully exposed behaviour of grains other than soybeans. In each case, predicted moisture ratios were closer to observed experimental values during the entire drying process with the modified Page's equation than they were with the basic logarithmic model such as that employed by Henderson and Pabis (1961) and Ross and White (1972).

Sharaf-Eldeen *et al.* (1979) found that a two-term exponential model utilising the concept of a dynamic moisture content was superior to the modified form of Page's equation in describing the drying behaviour of fully-exposed shelled maize, rough rice and soybeans. However, the modified Page's equation was found to provide a better description of the drying process than the basic logarithmic model.

d) Single Exponential Model (Henderson and Pabis Equation)

The Henderson and Pabis model is the first term of a general series solution of Fick's second law. This model has been used to model thin layer drying characteristics of various agricultural products (Chinnan, 1984; Henderson and Pabis, 1961). This can be written as:

$MR = \text{a} \exp(-kt)$..(2.6)

where;

a and *k* are drying constants, *t* is drying time in minutes.

CHAPTER THREE

MATHEMATICAL MODELLING OF DRYING OF JASMINE RICE UNDER FLUIDISED BED AND STATIC DRYING

3.1 Introduction

In this study, jasmine rice was dried using the two-stage drying technique. Rice samples were fast dried using a fluidised bed dryer (18-19% wb) and slowly dried to the storage moisture content (≤14% wb) using a static dryer. The second stage of drying also included drying some of the samples in the sun to 14% wb or lower.

A mathematical model is an important tool used to estimate the drying time of agricultural products, instead of conducting real experiments. So far, a number of mathematical models have been developed to describe the drying process of food grains. The Page's model and the Single Exponential model have been used to describe the drying data in this study.

3.2 Materials and Methods

3.2.1 Samples

The rice samples used for this experiment were that of jasmine rice variety. The paddy was obtained from the experimental plots of the Ministry of Food and Agriculture at Besease in the Ejisu/Juaben District of the Ashanti Region of Ghana. The rice samples were manually harvested and hand threshed to minimise crack development which occurs during mechanical threshing.

3.2.2 Sample conditioning

The paddy samples were manually cleaned to remove impurities such as leaves, broken stalks, immature seeds and unfilled seeds in order to obtain well-filled samples for the experiments. The cleaned samples were tightly sealed in polythene bags and stored in a refrigerator until needed.

3.2.3 Moisture content determination

The initial moisture content, MC (% wb) of the rice samples was determined using the standard oven method (ASAE, 1995). Four (4) replicates, each of about 15 g weight, were weighed using the Sartatrius Electronic Balance (L 22005). After pre-conditioning the oven to a temperature of 130°C, the samples were put in the oven for 24 h (ASAE, 1995). The final weights were obtained and an average of the four determined.

The initial moisture content was then calculated using equation 3.1.

$$\text{MC wb} = \frac{\text{initial weight} - \text{final weight}}{\text{initial weight}} \times 100\% \qquad (3.1)$$

where:

MC wb = moisture content in wet basis.

3.2.4 Drying experiments

Two dryer types were used in the experiments: a fluidised bed dryer and a fixed bed dryer. The fluidised bed dryer was expected to dry the samples from a high moisture level (20-25% wb) to 19% or below. The fixed bed dryer and sun drying were used for the second stage drying (to reduce MC from ≤19% wb to ≤14% wb).

3.2.4.1 Fluidised bed drying

A laboratory fluidised bed dryer (P. R. L. Engineering Ltd., UK, Model: FBD/L 72) was used in the experiment (Figure 3.1). The sample holder was about 17 cm high and 15.5 cm wide.

Figure 3.1 A laboratory fluidised bed dryer

The dryer had five main controls: power, temperature, heater, blower and speed regulator controls. An electronic balance was used to estimate the weight reduction intermittently.

3.2.4.2 Experimental conditions

The fluidised bed drying experiments in this study focused on drying high moisture paddy (of about 23% wb MC) down to ≤19% wb. This was carried out using three (3) temperatures: 60, 80 and 100°C. The experimental setup is presented in table 3.1.

Table 3.1 Conditions used in the fluidised bed drying

Replication	Condition			
	Initial MC%wb	**Temperature (°C)**	**Bed depth (cm)**	**Air flow rate (m/s)**
1	22.44	3 levels (60, 80, 100)	7	≈ 2.8
2	22.44	3 levels (60, 80, 100)	7	≈ 2.8
3	22.44	3 levels (60, 80, 100)	7	≈ 2.8
4	22.44	3 levels (60, 80, 100)	7	≈ 2.8

The initial mass of each sample before drying, was 370 g and of a bed depth of 7 cm.

3.2.4.3 Drying procedure

The samples due for drying were removed from the refrigerator and their temperature allowed to come to equilibrium with that of atmospheric temperature, resulting in a reduction in thermal stress during drying.

The fluidised bed dryer was the batch type, with a grain holder to contain the samples during the drying process. The dryer was preset to the required conditions before the samples were poured into the grain holder.

Each run lasted between 1, 2 and 4 minutes depending on the temperature. The reduction in weight was measured between runs. The moisture content was estimated using equation 3.2.

$$Mi = \left(1 - \frac{W_0(1-M_0)}{W_i}\right) \times 100\% \qquad (3.2)$$

where;

Mi = MC at ith time, %
M_0 = initial MC, decimal
W_0 = initial weight of sample, g
W_i = weight of sample at ith time, g

The drying runs were continued until an estimated moisture content of ≤19% wb was obtained.

In batch fluidised bed drying, both moisture content and temperature of samples were assumed to be uniform throughout the bed at any given time due to the high degree of mixing in the drying chamber.

3.2.4.4 Fixed bed drying

The fixed bed dryer or tray dryer (static dryer), fabricated in the Department of Agricultural Engineering of the Kwame Nkrumah University of Science and Technology, Ghana, was used in the second stage of drying (Figure 3.2). It has an electric fan that blows air over a heating element (1,800 W). The speed of heated air was measured using an anemometer (Wilh Lambreachf Gmbh, 3400 Gottingen, Germany). The samples were placed in trays and the initial weights recorded using electronic balance (Sartorius model).

Figure 3.2 Fixed bed dryer or tray dryer (static dryer)

3.2.4.5 Experimental conditions

The samples were dried at a tempering temperature of about 45°C and a fixed airflow rate of 1.3 m/s. Equilibrium moisture content, M_e was assumed to be relatively small (Thakor *et al.*, 1999). Moisture ratio needed for calculation of drying constants was calculated from equation 3.4.

3.2.4.6 Drying procedure

The samples that had been previously dried using the fluid bed dryer were then dried the second time using the fixed bed dryer to dry from ≤19% wb to ≤14% wb. The weights of the samples were measured at intervals of about 20 min and the MC (% wb) estimated using equation 3.2.

2.2.4.7 Sun drying

Some of the samples that had been previously dried using fluidised bed dryer were dried in the second stage using sun drying to ≤14% wb. The initial weight of samples was about 370 g and the depth was 5-10 cm. The moisture content reduction was estimated using equation 3.2.

3.2.4.8 Control

- Open sun drying of the Jasmine rice samples was done to serve as control. These samples were completely dried from the initial moisture content of about 25% wb using sun drying to ≤14% wb.
- This was considered because it was used to compare with the conventional drying employed by farmers in drying rice harvested from the farm.

3.2.5 Drying models

The moisture contents (db) of dried paddy obtained as described in section 3.2 were fitted into two thin layer drying models, including the Page's model and Single Exponential model. The details of these equations are found in section 2.4 of chapter two.

3.2.5.1 Mathematical modelling of thin layer drying curves

The moisture ratio (MR) of the dried paddy was calculated using equation 3.4.

$$MR = \frac{M_i - M_e}{M_o - M_e} \quad \text{...(3.3)}$$

where:

MR = Moisture Ratio (dimensionless)
M_i = Moisture content (%db) at any time
M_e = Equilibrium Moisture Content (%db)
M_o = Initial Moisture Content (%db)

The experiments took place under different environments. The values of M_e when computed were relatively small or negligible as compared to M_i or M_0 (Thakor *et al.*, 1999). Equation 3.3 can therefore be simplified to equation 3.4.

$$MR = \frac{M_i}{M_o} \qquad (3.4)$$

3.2.5.2 Determination of drying constants

The two thin layer drying equations were transformed for the determination of the constants as follows:

a) Page's model

$$MR = \exp(-kt^n) \qquad (2.3)$$

The equation can be transformed as follows:

$$-\ln(MR) = kt^n$$
$$\therefore \ln(-\ln(MR)) = \ln k + n \ln t \qquad (3.5)$$

Equation (3.5) is in the form of a straight line. The relationship is as follows:

$y = \ln(-\ln MR)) = MR,$
$m = n,$
$x = \ln t$ and
$c = \ln k.$

Equation (3.5) can therefore be written as:

$MR = \ln k + n \ln t$..(3.6)

b) Single Exponential (Henderson and Pabis) equation

The equation is expressed as:

$MR = \mathrm{a}\exp(-kt)$..(2.6)

It can also be simplified to the form;

$\ln MR = \ln a - kt$..(3.7)

The equation above is also in the form of a straight line and they relate as follows:

$y = \ln MR,$
$m = -k,$
$x = t$ and
$c = \ln a.$

3.2.6 Analysis of drying data

The Page's model has been used to accurately simulate the drying curves of rough rice (Iguaz *et al.*, 2003), potato slices (Akpinar *et al.*, 2003), green bean, potato and pea (Senadeera *et al.*, 2003), carrot (Doymaz, 2004; Misra and Brooker, 1980; Ross and White, 1972; White *et al.*, 1973). The Single Exponential model has also been used to model thin layer drying characteristics of various agricultural products (Chinnan, 1984; Henderson and Pabis, 1961).

To determine the constants k and n, linear regression of equation 3.6 was carried out using the trend function in Excel spreadsheet to determine the constants (Figure 3.21). A similar method was used to determine the constants a and k of equation 3.7. (Figure 3.22). The root mean error (RME) and the root mean square error (RMSE) between the experimental and predicted values were calculated using equations (3.8) and (3.9) respectively.

3.2.7 Fitness of the models

The thin layer drying models were fitted with the drying data to predict the moisture ratio (MR). The criteria used to select the best model that fitted the data well was the coefficient of determination, R^2, the root mean error (RME) and root mean square error (RMSE).

The RME was calculated using equation 3.8.

$$RME = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|\left(MR_{\exp,i} - MR_{cal,i}\right)\right|}{MR_{\exp,i}} \quad \text{.......................................(3.8)}$$

Equation 3.9 was applied to calculate RMSE.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{cal,i}\right)}{N}} \quad \text{...(3.9)}$$

where;

N = number of observations

$MR_{\exp,i}$ = experimental moisture ratio at i^{th} observation

$MR_{cal,i}$ = calculated moisture ratio at i^{th} observation

3.3 Results and Discussion

The two-stage drying concept was used and the results obtained from the drying experiments are presented below. Figures 3.3 and 3.4 compare the reduction in MC of the various drying temperatures (60°C, 80°C and 100°C) using the fluidised bed and followed by fixed bed or sun-drying in the second stage of drying.

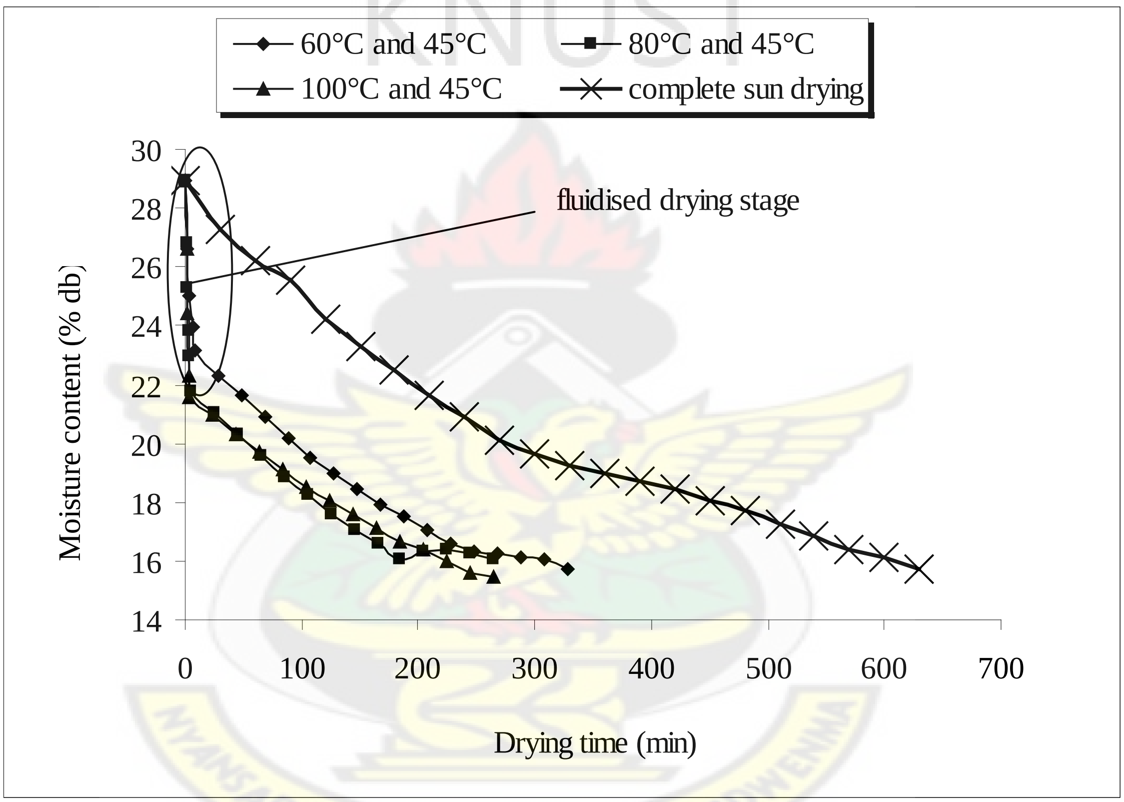

Figure 3.3 Fluidised bed drying at 60°C, 80°C and 100°C and fixed bed drying

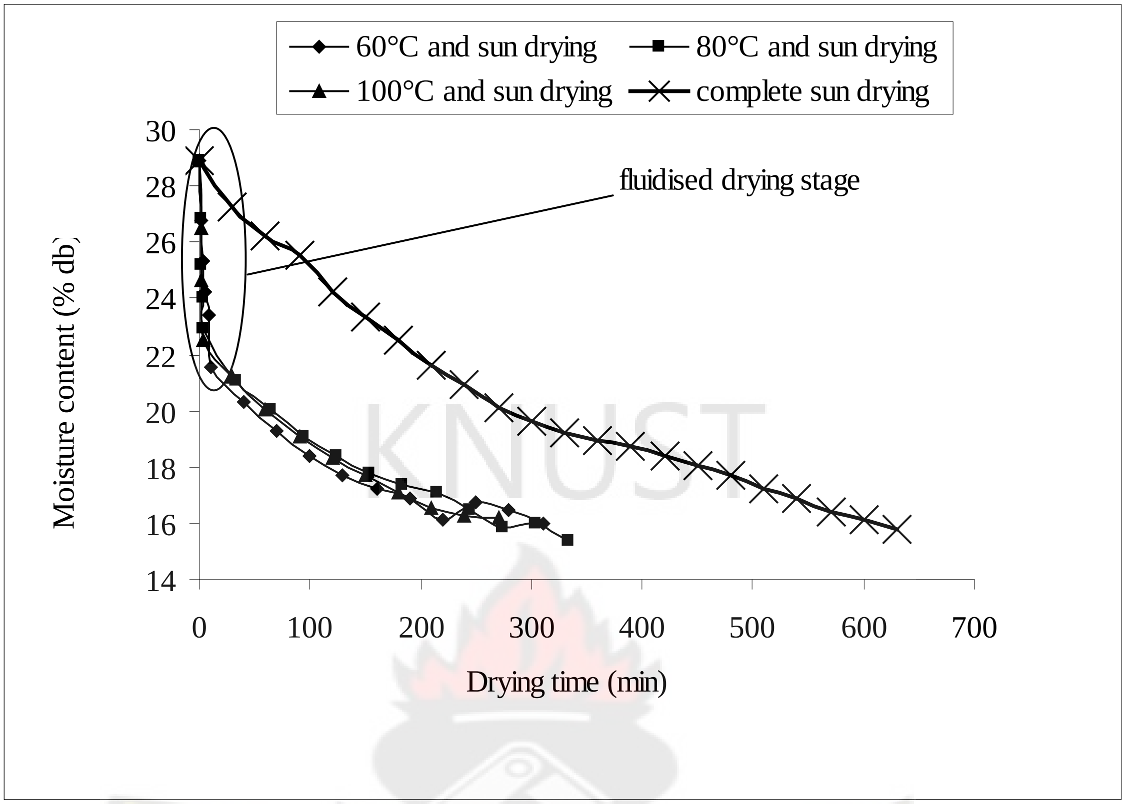

Figure 3.4 Fluidised bed drying at 60°C, 80°C and 100°C and sun drying

Clearly, it can be realised that (Figure 3.3), moisture reduction in the case of the complete sun drying had a longer exposure than the fluidised and fixed bed drying. It can also be seen from Figure 3.4 that, when sun drying was employed to dry paddy during the second stage, there was an extended time of drying to reach the storage moisture content. Drying at 60°C took the longest time as compared to the other two temperatures employed.

Graphical comparisons of the two experimental and predicted moisture ratios from the Page and Single Exponential models are shown in Figures 3.5 to 3.18.

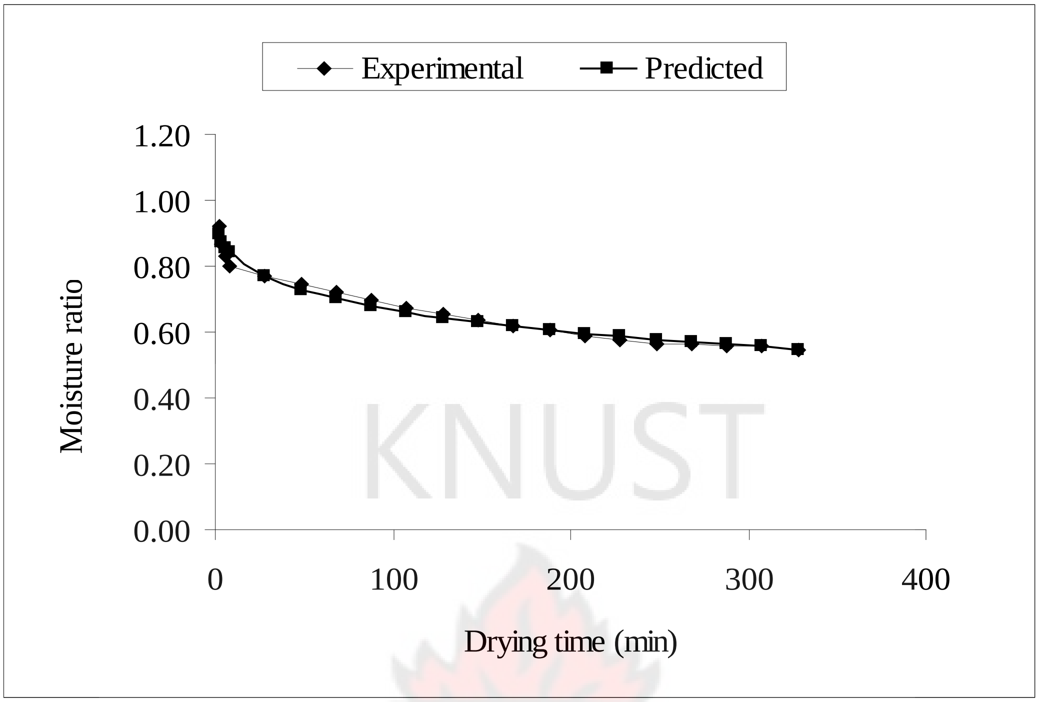

Figure 3.5 Experimental and predicted moisture ratios (using Page model) of Jasmine rice using fluidised bed drying at 60°C and fixed bed drying at 45°C

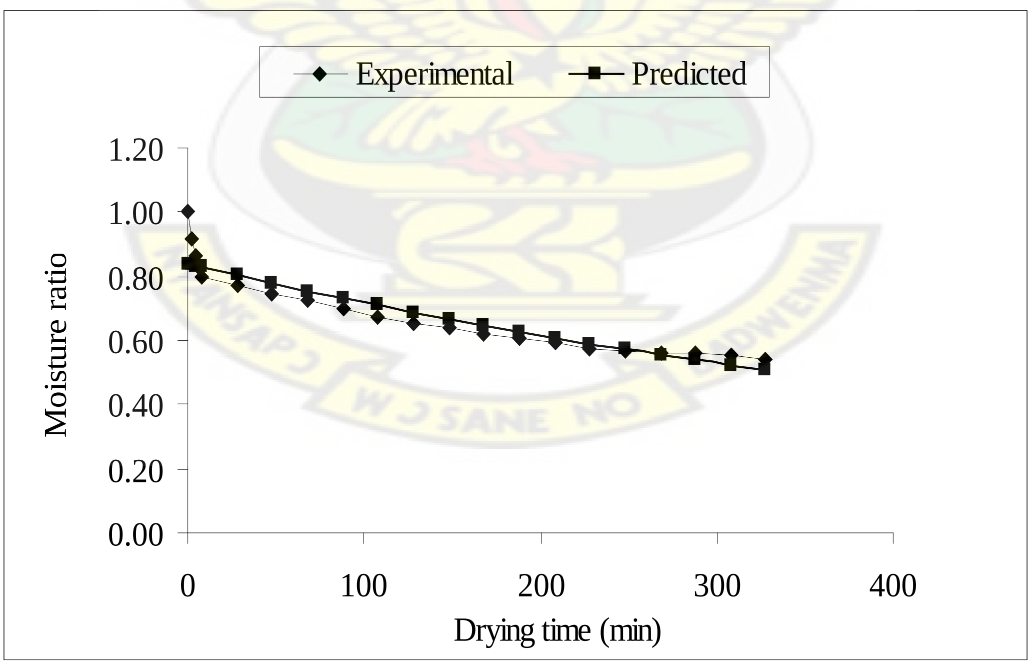

Figure 3.6 Experimental and predicted moisture ratios (using Single Exponential model) of Jasmine rice using fluidised bed drying at 60°C and fixed bed drying at 45°C

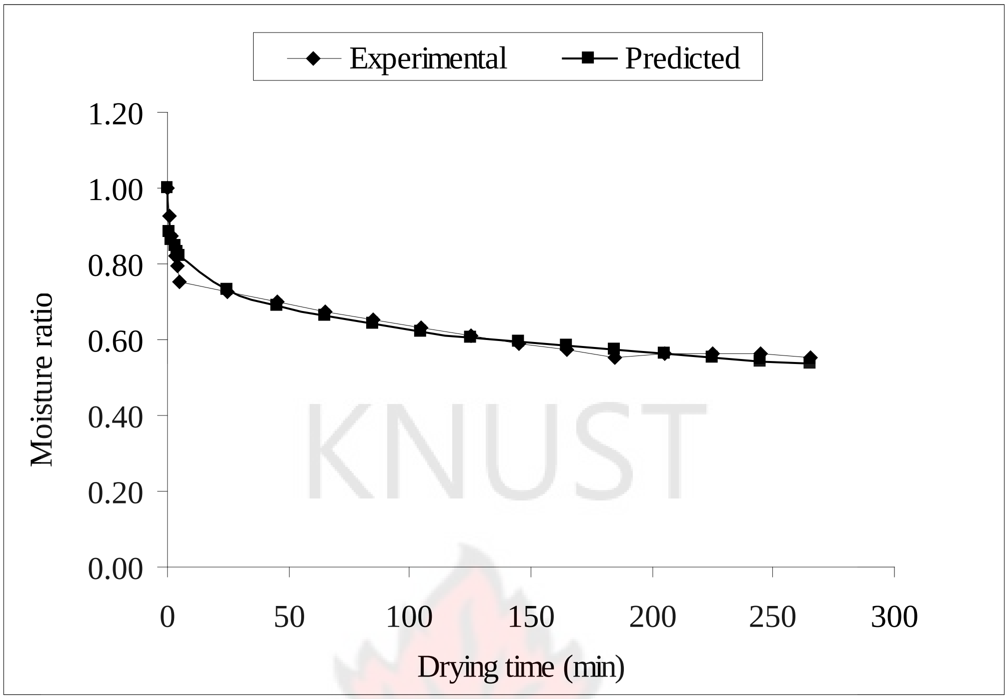

Figure 3.7 Experimental and predicted moisture ratios (using Page model) of Jasmine rice using fluidised bed drying at 80°C and fixed bed drying at 45°C

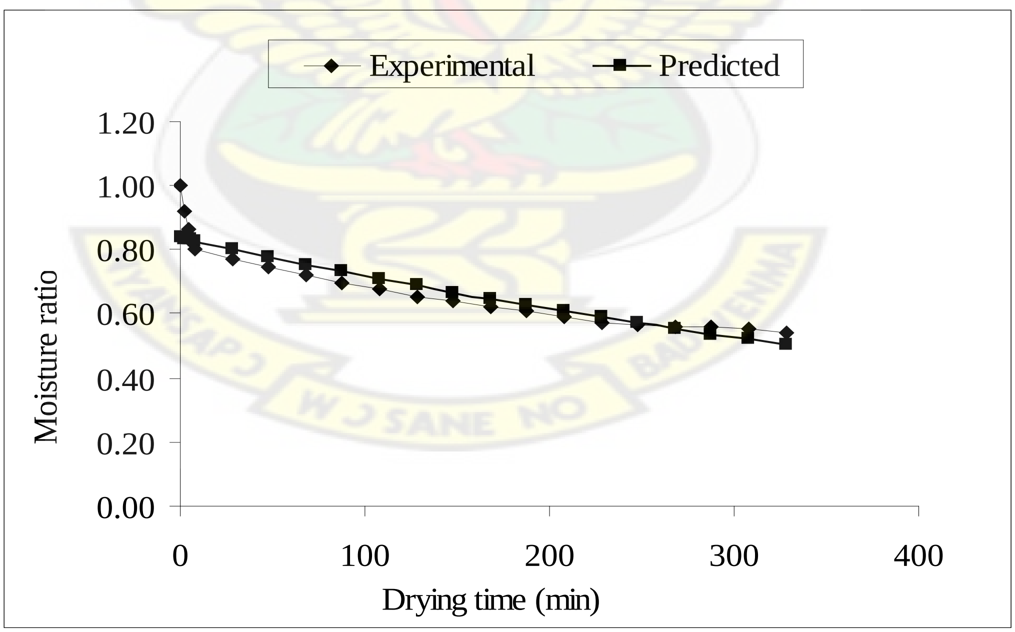

Figure 3.8 Experimental and predicted moisture ratios (using Single Exponential model) of Jasmine rice using fluidised bed drying at 80°C and fixed bed drying at 45°C

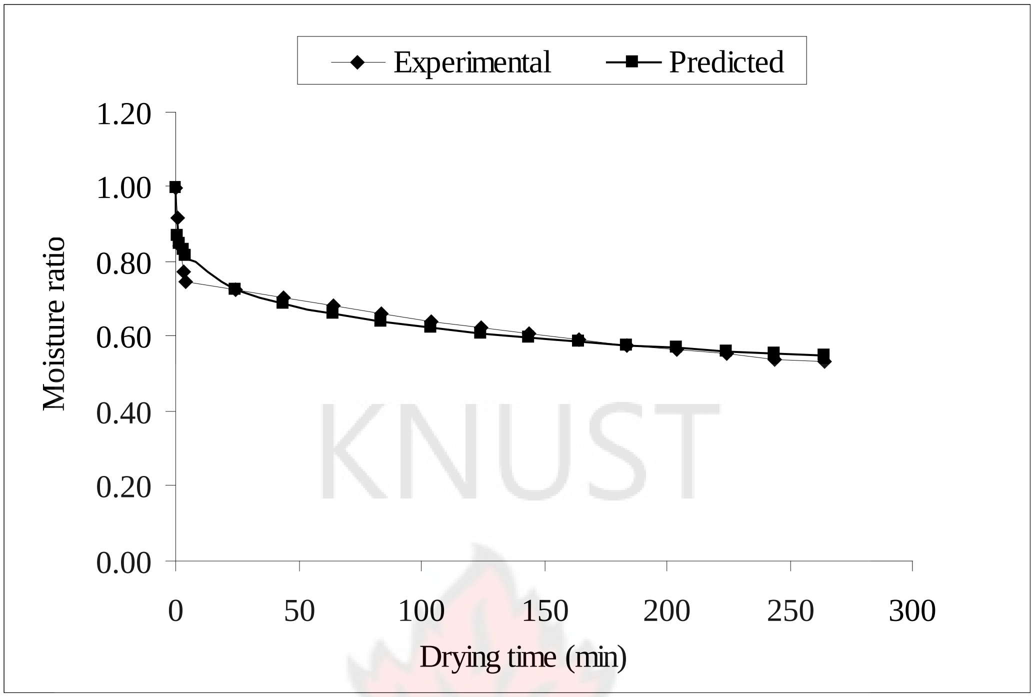

Figure 3.9 Experimental and predicted moisture ratios (using Page model) of Jasmine rice using fluidised bed drying at 100°C and fixed bed drying at 45°C

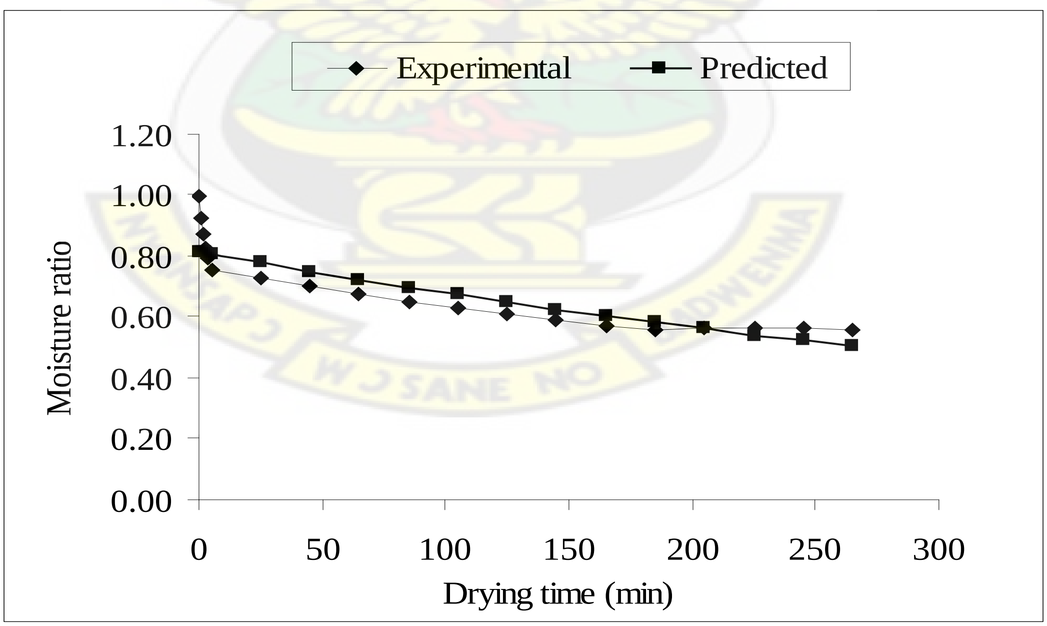

Figure 3.10 Experimental and predicted moisture ratios (using Single Exponential model) of Jasmine rice using fluidised bed drying at 100°C and fixed bed drying at 45°C

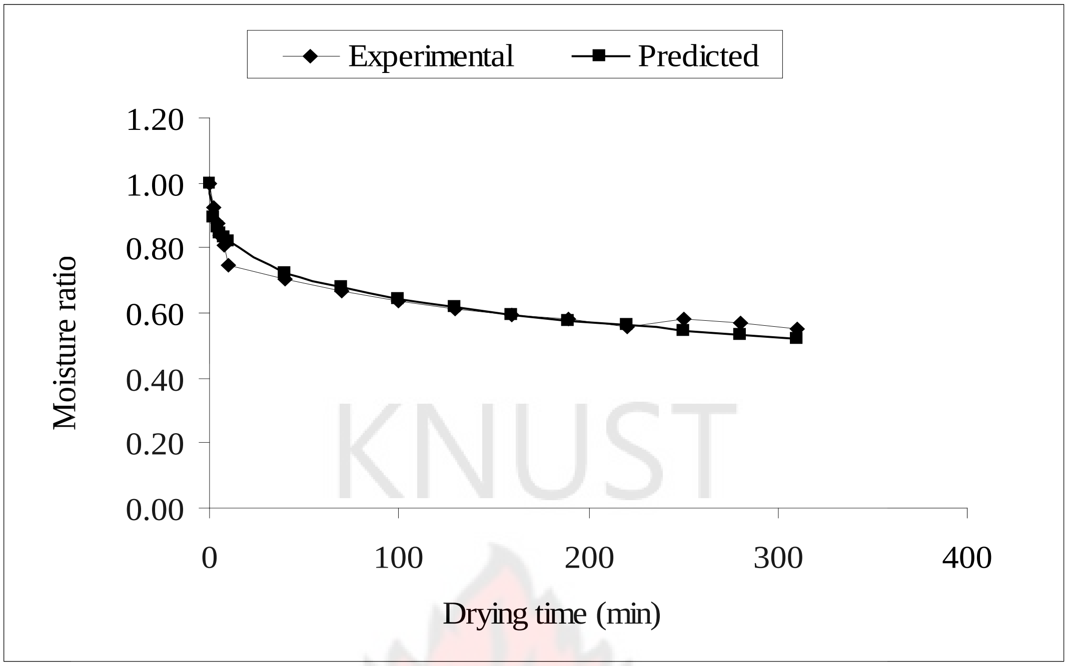

Figure 3.11 Experimental and predicted moisture ratios (using Page model) of Jasmine rice using fluidised bed drying at 60°C and sun drying

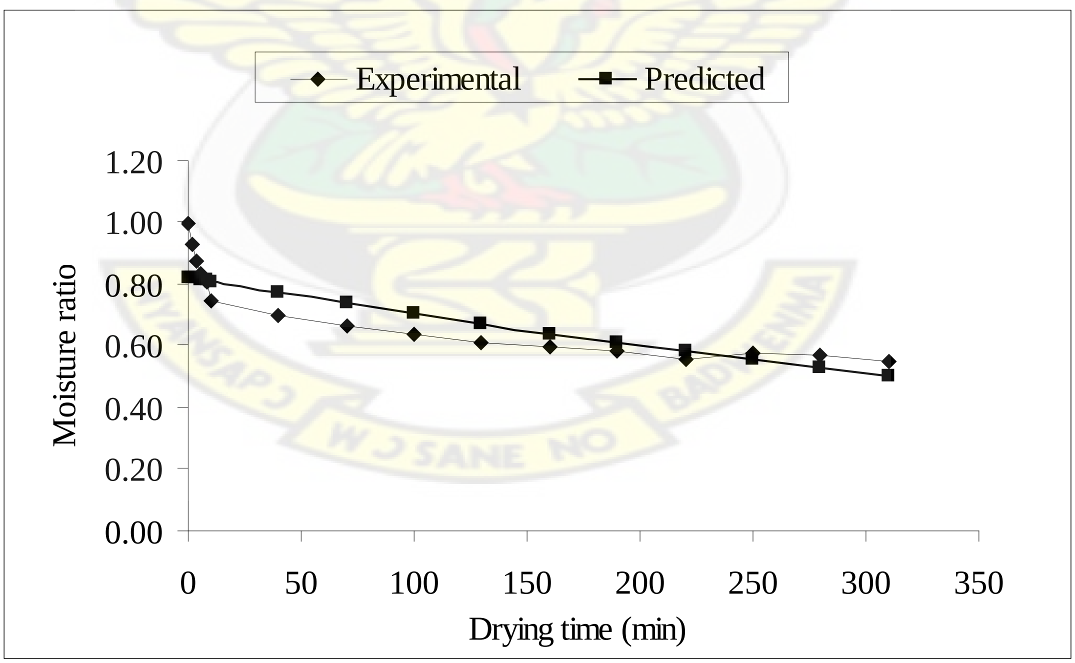

Figure 3.12 Experimental and predicted moisture ratios (using Single Exponential model) of Jasmine rice using fluidised bed drying at 60°C and sun drying

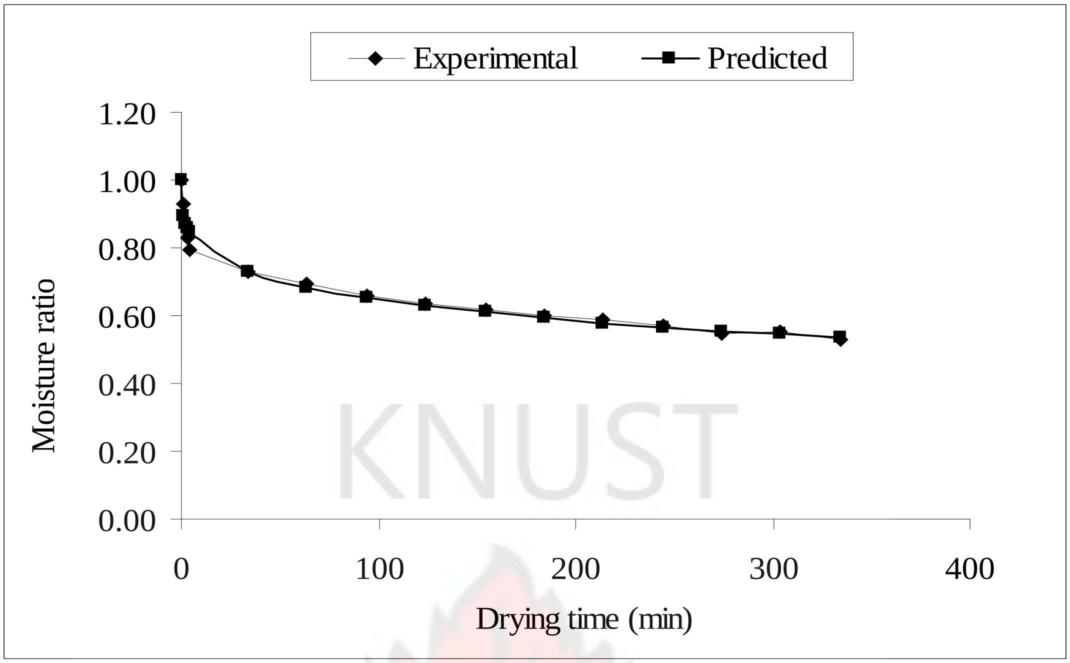

Figure 3.13 Experimental and predicted moisture ratios (using Page Model) of Jasmine rice using fluidised bed drying at 80°C and sun drying

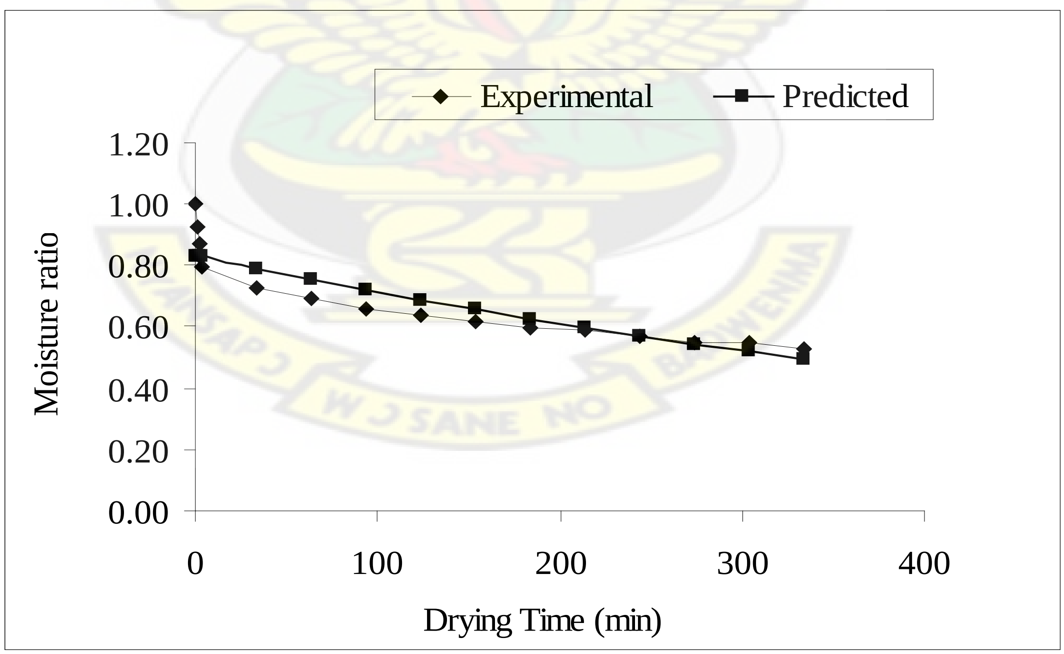

Figure 3.14 Experimental and predicted moisture ratios (using Single Exponential model) of Jasmine rice using fluidised bed drying at 80°C and sun drying

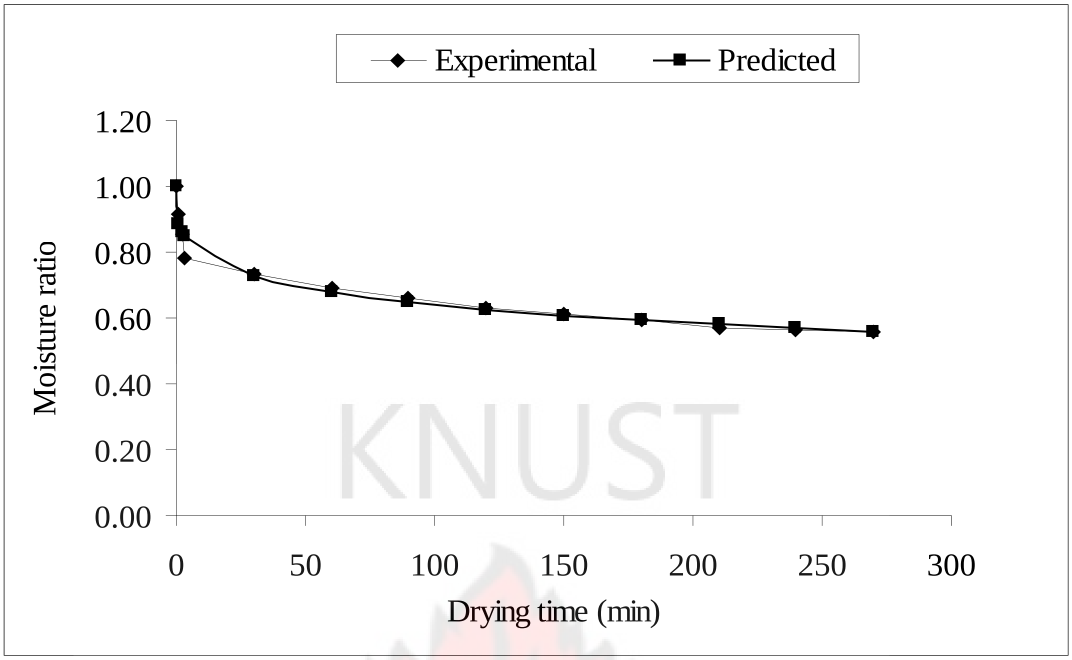

Figure 3.15 Experimental and predicted moisture ratios (using Page model) of Jasmine rice using fluidised bed drying at 100°C and sun drying

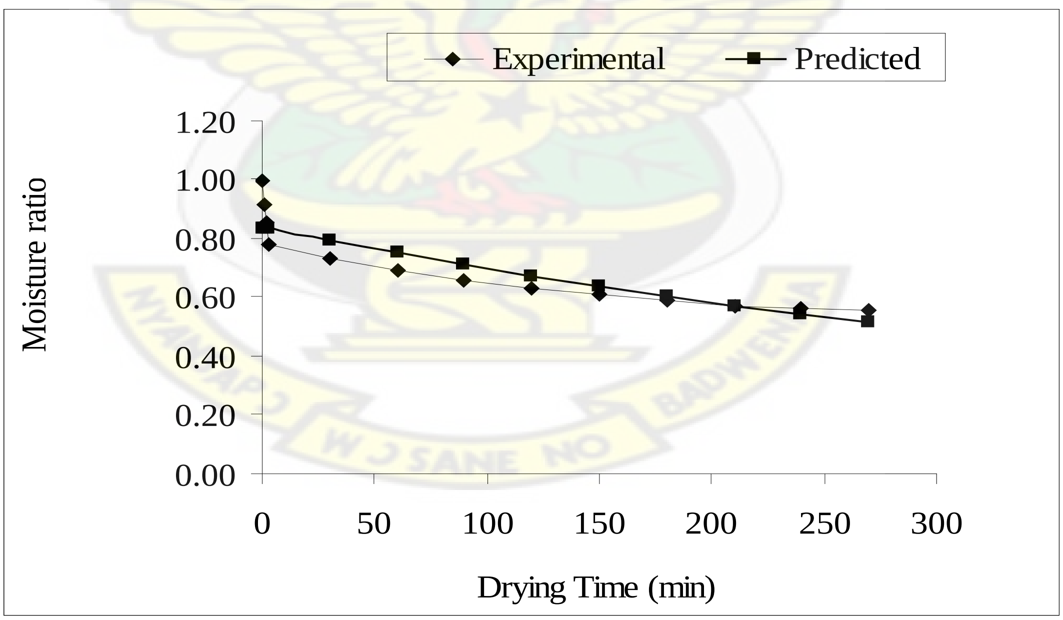

Figure 3.16 Experimental and predicted moisture ratios (using Single Exponential model) of Jasmine rice using fluidised bed drying at 100°C and sun drying

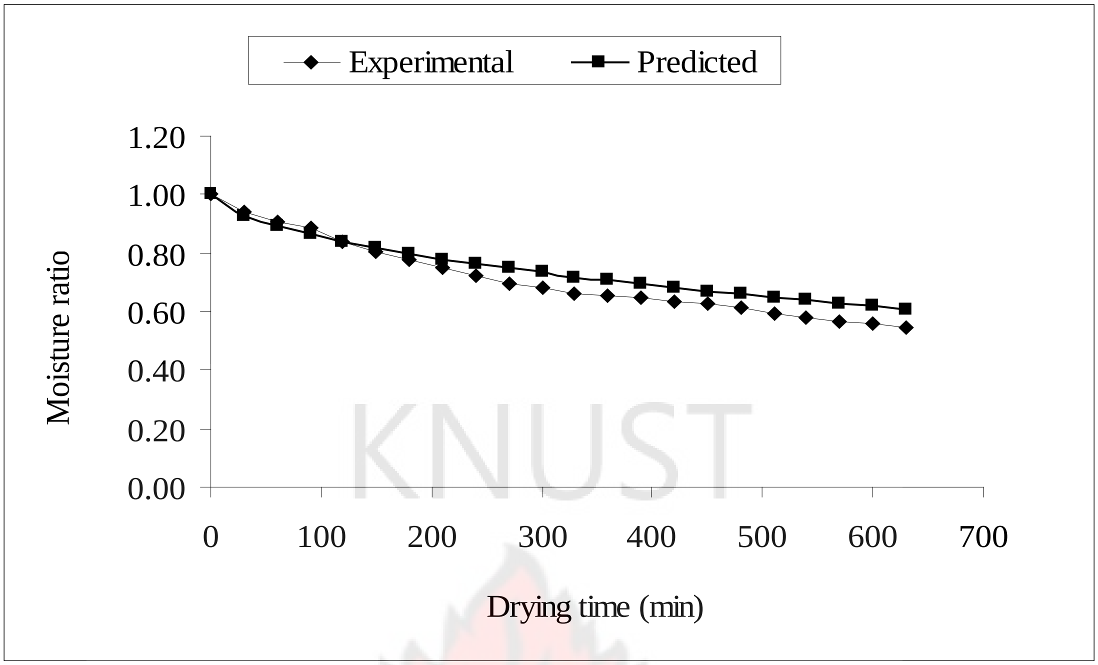

Figure 3.17 Experimental and predicted moisture ratios (using Page model) of Jasmine rice using total sun drying as a control

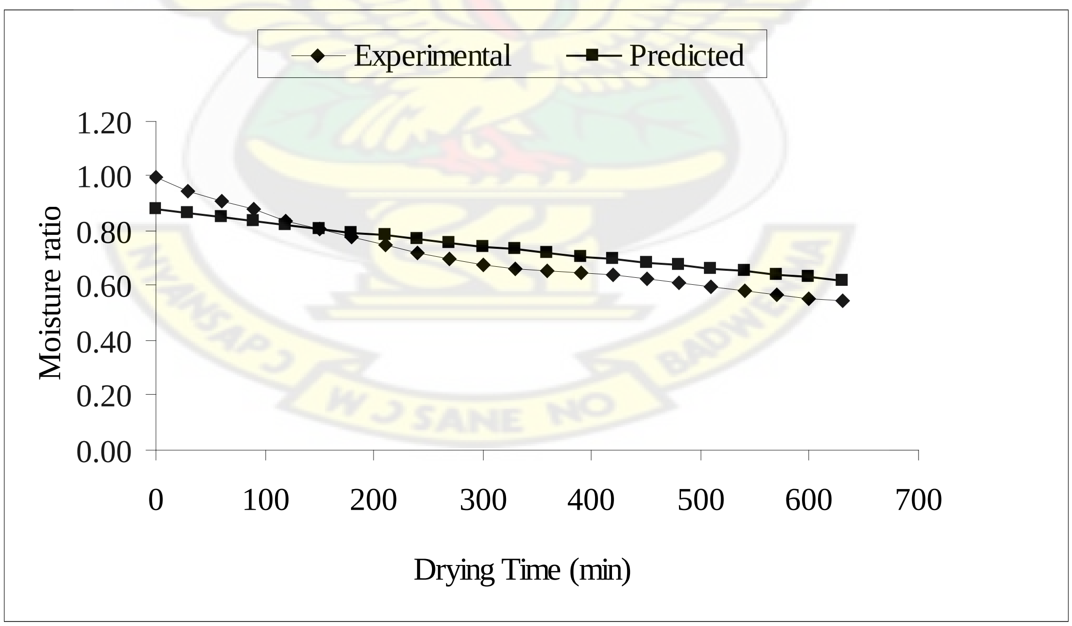

Figure 3.18 Experimental and predicted moisture ratios (using Single Exponential model) of Jasmine rice using total sun drying as a control

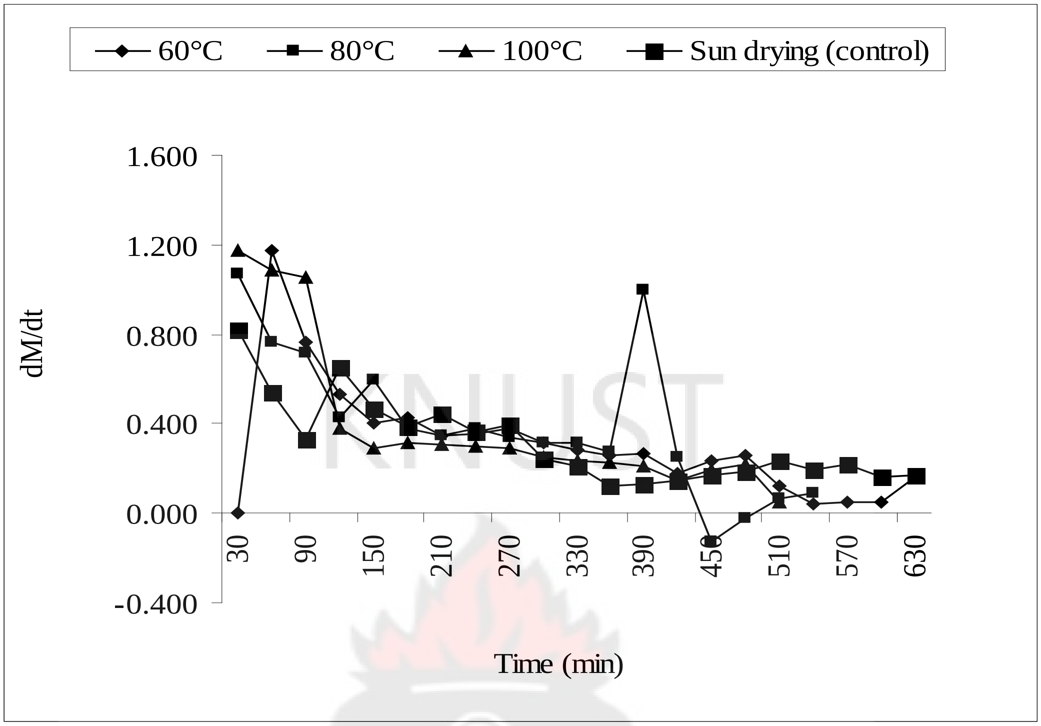

Figure 3.19 Effects of drying temperature on drying rate (fluidised and fixed bed drying)

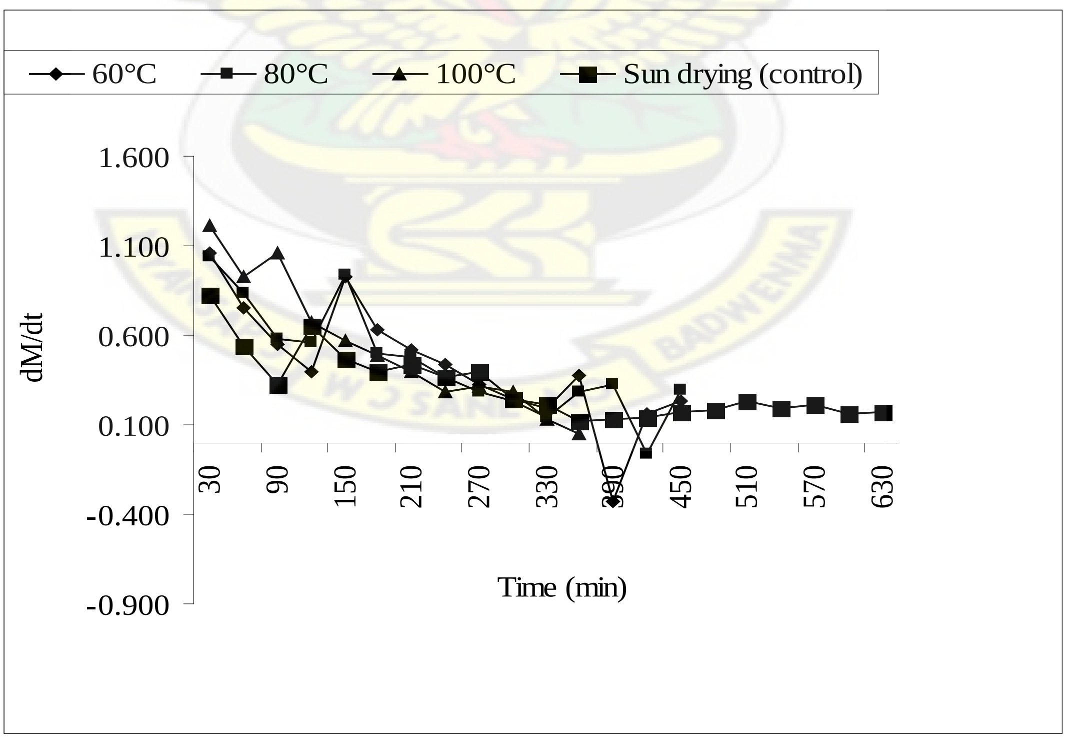

Figure 3.20 Effects of drying temperature on drying rate (fluidised and sun drying)

During the first stage of drying, the rate of moisture reduction increased as temperature increased from 60°C to 100°C. Figures 3.5-3.10 show the comparison between the predicted moisture ratio and experimental ratio. In this case fluidised bed dryer was used in the first stage and a fixed bed dryer used in the second stage of drying. Moisture content reduced from 28.93 to 23.17% db between 4 min and 8 min to 21.56% db. The grains were therefore exposed to a shorter period of drying. The fast rate of drying is consistent with the fundamental drying theory, which expects a higher heat transfer flux to the bed of paddy with higher temperature. It could also be due to the high heat and mass transfer rates between the air and the kernels due to the high air velocity (Brooker *et al*. 1992). The drying rate constant, *k*, also increased from 0.08672/h to 0.139264/h (Table 3.2). Other researchers such as Patil and Ward (1989) explained that the high drying rate at the high initial moisture contents of rapeseed is due to the availability of more moisture at the surface of the grain. They also reported that, the faster rate of drying was due to the greater sensible heat in the drying air. At lower initial moisture content, the moisture has to be transferred from the interior of the grain to the surface (Meas, 1999).

The second stage of drying where a slow rate dryer was used witnessed a slow reduction in moisture content (240 to 300 min) when compared with the first stage of drying, which was less than 10 min. As the grain moisture content reduced, the rate at which it lost moisture also reduced.

Figures 3.11 to 3.16 are graphs where fluidised bed drying was employed in the first stage and sun drying employed during the second stage of drying. Where the temperature of drying using the fluid bed drying was 60°C, it took about 270 min to dry to the storage moisture content using sun drying in the second stage. A temperature of 100°C in the first stage and sun drying in the second stage, took about 240 min. This indicates that, the 100°C took less time to dry in the second stage. This was due to the higher sensible heat in the first stage. The exposure time during this phase was longer than when the static dryer was employed.

However, when paddy was dried in the sun, from the initial moisture content to the storage moisture content, it took up to about 630 min (Figures 3.17 and 3.18). One could therefore conclude that, drying paddy using the two-stage drying dried faster than the conventional sun drying employed by farmers in Ghana.

Figure 3.19 is a plot of the effect of drying rate against temperature for fluidised and fixed bed drying. The plots are means of the four replications. The drying rate initially had a fast reduction during the fluidised bed drying because of the higher temperatures used at that stage. The second stage of drying was relatively a tempering stage where a temperature of 45°C was used. The rate of drying here was relatively uniform. When sun drying was employed during the second stage (Figure 3.20), the drying rate was not uniform from that point onwards. This could be attributed to the changes in air temperature during the drying process.

3.3.1 Application of the Page model in the determination of the drying constants (*k* and *n*)

Values of the drying constants, the coefficient of determination (R^2) the RME and RMSE between the experimental and the predicted moisture ratios are presented in Table 3.2. The drying constants *k* and *n* and R^2 were determined from figure 3.21.

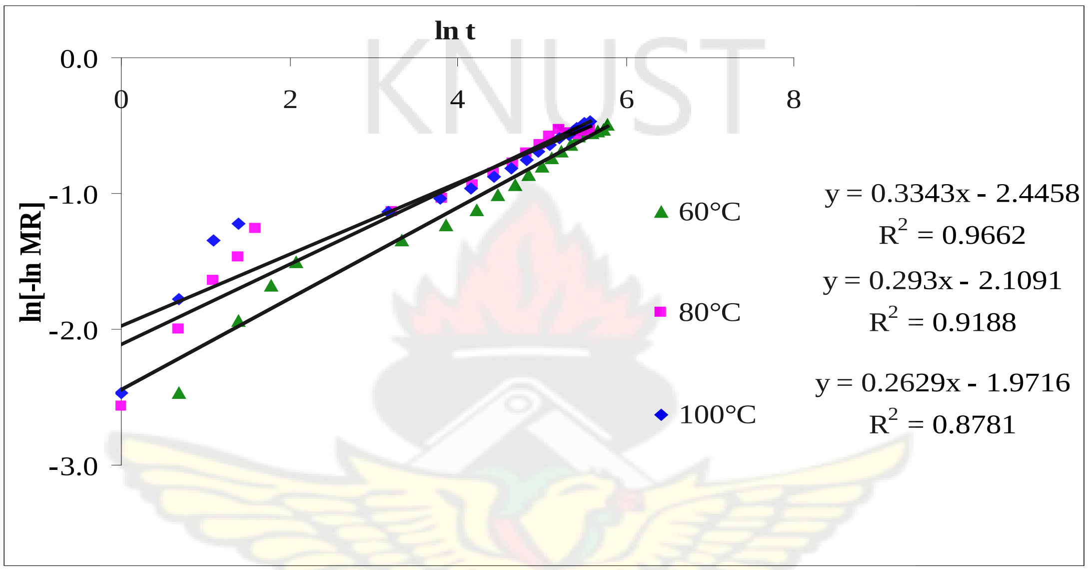

Figure 3.21 Relationship between moisture ration and drying time for fluidised and fixed bed drying of page model

Table 3.2 The drying constants of *k*, *n*, R^2, RME and RMSE using Page model

Temperature (1st and 2nd drying)	k (h^{-1})	n	R^2	RME ($\times10^{-4}$)	RMSE ($\times10^{-4}$)
60°C 1st, 45°C 2nd	0.08672	0.334338	0.96626	9.2127	6.1185
80°C 1st, and 45°C 2nd	0.121344	0.292969	0.91890	70.10	40.11
100°C 1st and 45°C 2nd	0.139264	0.262837	0.87801	118.84	61.91
60°C 1st and sun drying	0.09014	0.344377	0.92899	55.388	32.692
80°C 1st and sun drying	0.11063	0.297521	0.94365	36.508	21.36
100°C 1st and sun drying	0.12360	0.277989	0.92437	103.45	34.18
Complete sun drying	0.008630	0.628176	0.86235	2086.0	1569.29

The coefficient of correlation (R^2), the root mean error (RME) and the root mean square error (RMSE) were the primary criteria used for selecting the best equation which well fits the data. A higher value of R^2 is an indication of a good fit. However, lower values of RME and RMSE give an indication of good fit for a particular equation.

The Page model gave higher R^2 values of 0.96626 to 0.86235. The Single Exponential model had values of 0.89123 to 0.62460 (Table 3.3). These values were lower than that from the Page model indicating a better fit for the Page model. The RME were between 9.2127×10^{-4} and 2086.0×10^{-4} whilst RMSE values were between 6.1185×10^{-4} and 1569.29×10^{-4}. The RME from the Single Exponential model were 119.052×10^{-4} and 1895.0×10^{-4}. The RMSE had values of between 79.07×10^{-4} and 1394.29×10^{-4}. From the above outcome, it was concluded that the Page equation gave smaller values of RME and RMSE, giving an indication that it fitted the data well and had good predictions of moisture ratio. The Page model has been used to accurately to simulate the drying curves of rough rice (Iguaz *et al.*, 2003).

3.3.2 Application of the Single Exponential model in the determination of the drying constants (*k* and *a*)

RME and RMSE were calculated using equation 3.8 and 3.9 respectively. The drying constants *k*, *a* and R^2 were determined from figure 3.22. These have been presented in Table 3.3. Moisture ratio was predicted using the Single Exponential model. Generally, the results showed that the Page model gave a better prediction than the single exponential equation as already indicated.

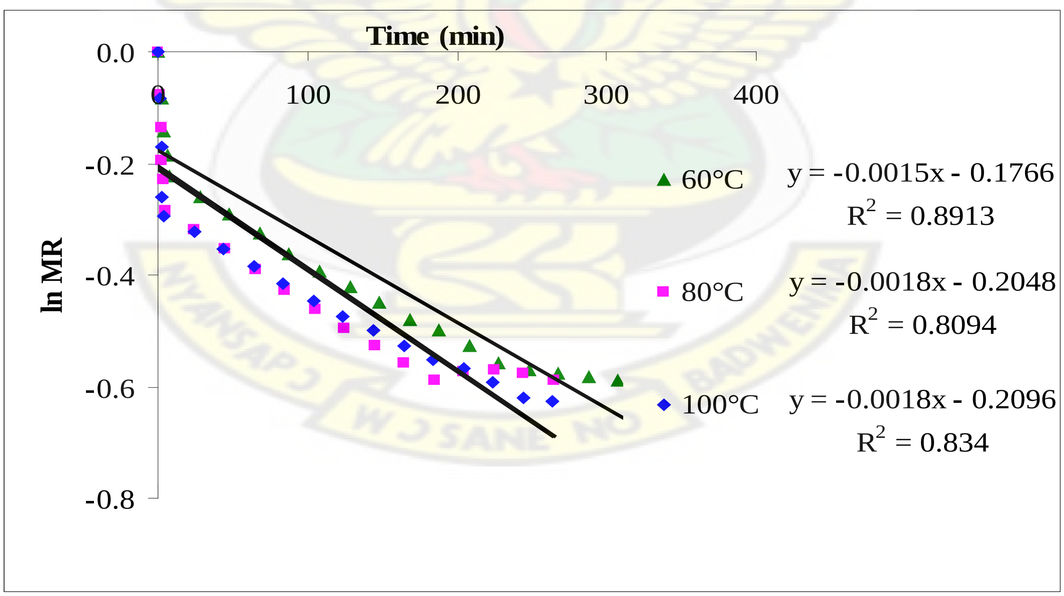

Figure 3.22 Relationship between moisture ratio and drying time for fluidised and fixed bed drying of Single Exponential model

Table 3.3 The drying constants *k*, *a*, R^2, RME and RMSE using the Single Exponential model

Temperature (1st and 2nd drying)	k (h^{-1})	a	R^2	RME ($\times 10^{-4}$)	RMSE ($\times 10^{-4}$)
60°C 1st, 45°C 2nd	0.00154	0.8380	0.89123	119.052	79.07
80°C 1st, and 45°C 2nd	0.001822	0.8149	0.80964	207.91	118.98
100°C 1st and 45°C 2nd	0.001812	0.8109	0.83434	196.94	102.59
60°C 1st and sun drying	0.00158	0.8224	0.78307	313.02	140.77
80°C 1st and sun drying	0.00156	0.8327	0.84885	232.94	103.82
100°C 1st and sun drying	0.00180	0.8352	0.82723	287.87	95.11
Complete sun drying	0.00055	0.8782	0.62460	1895.0	1394.29

3.3.3 Activation energy

The *k* values determined from the Page and single exponential model for the two-stage drying method were plotted against the reciprocal of absolute temperature to determine activation energy.

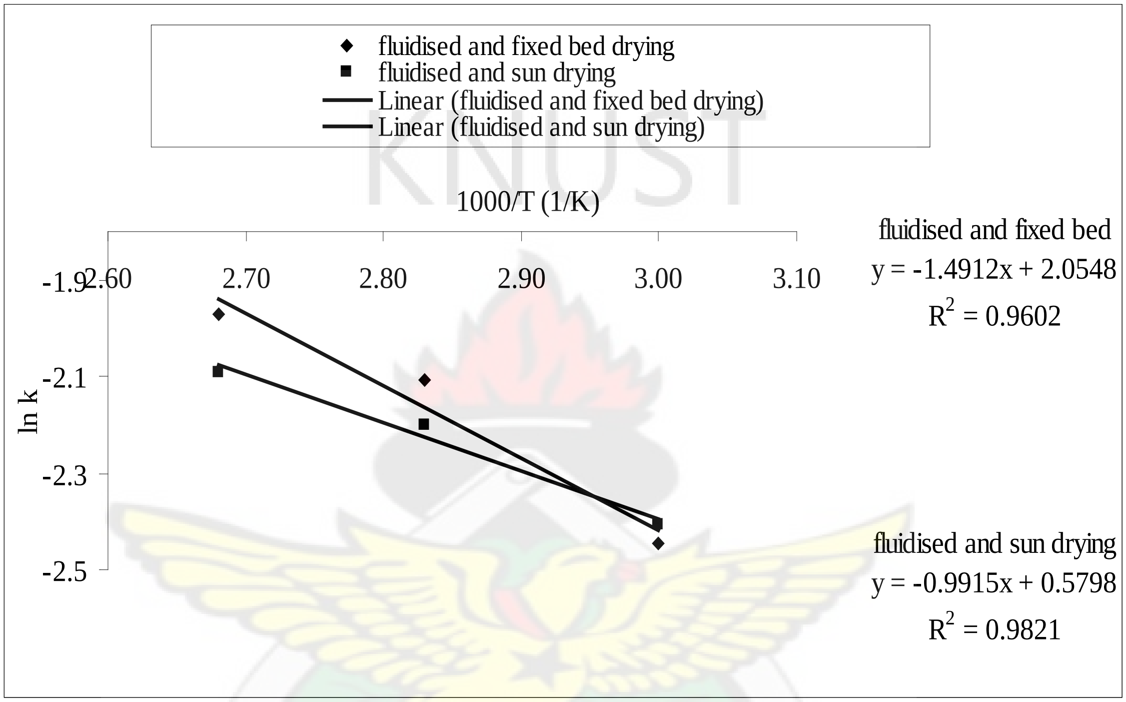

Figure 3.22 Arrhenius relationship between drying constant (from page equation) and temperature

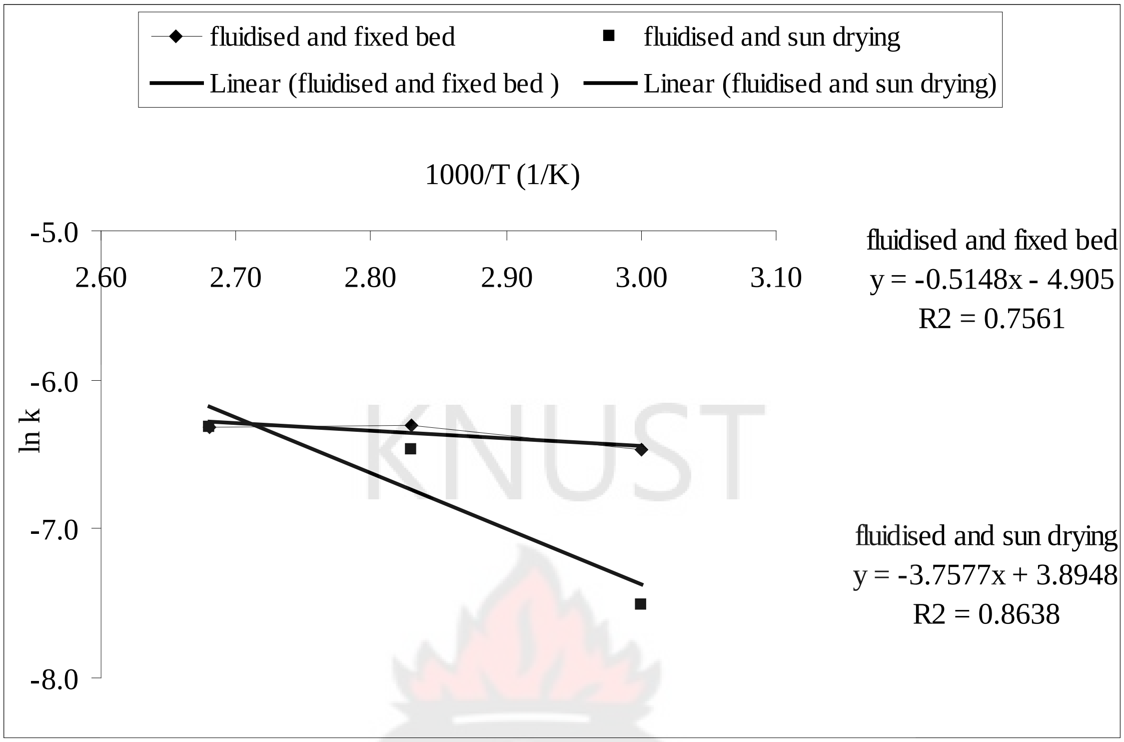

Figure 3.23 Arrhenius relationship between drying constant (from single exponential equation) and temperature

The activation energy for diffusion was estimated using the simple Arrhenius equation as given below (Addo *et al*., 2009).

$$k = k_o \exp\left(-\frac{E}{RT}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3-10)$$

where,

k = rate constant (h^{-1})

E = activation energy ($kJ{\cdot}mol^{-1}$)

k_o = frequency factor (h^{-1})

R = universal gas constant, 8.314×10^{-3} ($kJ{\cdot}mol^{-1}{\cdot}K^{-1}$)

T = absolute temperature (K)

A plot from the present work is as shown in Figures 3.22 and 3.23 and confirmed the proposed relationship between the drying constant and temperature (R^2 = 0.960 and 0.982,) for the page model. From graphs, activation energy was calculated as 12.388 × 10^{-3} kJ/mol and 8.231 × 10^{-3} kJ/mol for fluidised and fixed bed and fludised and sun drying respectively. Their response to temperature was therefore varying since the activation energy was sparsely spaced. The computed values of k_o were 7.805 $h^{-1}$and 1.785 h^{-1} for fluidised and fixed bed drying respectively. The activation energies were 4.24 and 31.18 kJ/mol for fluidised and fixed bed and then fluidised and sun drying respectively.

The calculated values of k_o were 0.007 and 49.14 h^{-1} respectively. According to Kashaninejad *et al.*, 2007, the activation energy is the barrier that must be overcome in order to activate moisture diffusion. By increasing the temperature and hence the drying rate this energy barrier can easily be overcome relatively, but there should be a compromise between high temperature and acceptable product quality (Kashaninejad *et al.*, 2007).

3.4 Conclusion

The results and observations of the drying experiments in this study suggest that fluidised bed drying is an efficient method of rapidly reducing the moisture content of harvested paddy to manageable levels. The findings of the study have been summarised below:

1. At the first stage of drying where a fluidised bed dryer was used, moisture reduction was rapid. It took about 4 to 8 min to reduce the moisture to 18% wb and below.
2. It took comparatively more time (between 240 to 300 min) to dry the paddy from 21.56 to 14% db and below when compared with the first stage of drying.
3. At the second stage of drying where a fixed bed dryer was used the drying rate constant, *k*, increased from 0.08672/h to 0.139264/h when the Page equation was used to predict the moisture ratio as the temperature increased from 60ºC to 100ºC. The values from the Single Exponential equation were not consistent.
4. When the temperature of drying using the fluid bed drying was 60°C, it took about 270 min to dry to the storage moisture content using sun drying in the second stage. A temperature of 100°C in the first stage and sun drying in the second stage, took about 240 min. However, when paddy was dried in the sun, from the initial moisture content to the storage moisture content, it took up to about 630 min.
5. The Page model described the data better than the Single Exponential model. It had higher R^2 values of between 0.96626 to 0.86235 and lower values of RME and RMSE of 9.2127×10^{-4} and 2086.0×10^{-4} and 6.1185×10^{-4} and 1569.29×10^{-4} respectively.
6. Activation energy was calculated as 12.388×10^{-3} kJ/mol and 8.231×10^{-3} kJ/mol for fluidised and fixed bed, and fluidised and sun drying respectively.

CHAPTER FOUR

CHANGES IN MILLING QUALITY OF JASMINE RICE DURING STORAGE

4.1 Introduction

The percentage of head rice and the whiteness of the milled rice are significant indices of the rice milling quality. Wongpornchai *et al.*, (2004) carried out a research on the aroma and milling quality of rice and found out that, on average, the percentages of whiteness of milled rice were 44.30% and 44.79% as obtained from paddy dried by high temperature hot air (70ºC) and modified air at 30ºC respectively. They found a slight variation in the percentage of whiteness obtained from each drying treatment with storage time. Cracking does not occur immediately after heated air drying (Sharma and Kunze, 1982). In their experiments, not much kernel cracking was detected immediately after drying for two, ten and twenty-four hours at 60ºC. Instead, most cracks were found occurring forty-eight hours after drying but were stable within a week of airtight storage.

4.2 Materials and Methods

4.2.1 Storage of dried paddy

The dried paddy samples were sealed in polythene bags and stored at room ambient conditions for one, three and six months. The rational was to assess the quality of the paddy after being dried for the storage period. A number of literature indicated that cracking of dried paddy is high immediately after drying but reduces as time goes on (Wongpornchai *et al.* 2004, Sharma and Kunze, 1982 and Minkah, 2006).

4.2.2 Milling of dried paddy

Milling of paddy took place for the first month (April, 2008), the third month (June, 2008) and the sixth month (September, 2008). The milling process involved three stages: dehusking, polishing and grading. Milling was carried out at the Rice Processing Laboratory of the Ghana Irrigation Development Authority, Ashaiman, Greater Accra Region of Ghana.

The moisture content of the samples at milling was read from a grain moisture tester (Riceter J301). Samples of 500g each were weighed before being loaded into the hopper of the Satake Rice Dehusking Machine for dehusking of the dried paddy to obtain brown rice (BR) (Figure 4.1).

Figure 4.1 A Satake Rice Dehusking Machine

The brown rice was again weighed before being loaded into the Satake Rice Polisher (Figure 4.2) to obtain polished rice (white rice, WR) the weight of which was also taken to be used for the determination of head rice. The Polisher was set to low-medium whiteness level. An average time of 3 min was used for each polishing process.

Figure 4.2 Satake Rice Polisher

The Satake Test Rice Grader was used to separate the broken rice kernels from the whole rice after milling (Figure 4.3). The rotating drum of the grader was set at an angle of 30° for the separation. The whole rice and the broken rice were weighed and recorded.

Figure 4.3 Satake Test Rice Grader

4.2.3 Analysis of milling data

The main quality test for milled rice was the Head Rice Yield (HRY) which is the mass percentage of rough rice kernels that remain as head rice, or rice that is three-fourths of a kernel length or longer after milling (USDA 1997).This was determined from equation 3.10.

$$\text{Head Rice Yield} = \frac{\text{weight of head rice}}{\text{total grain weight}} \quad \text{...(3.10)}$$

Measurements of weights were repeated at least twice to obtain average values. The HRY of the samples dried at 60°C, 80°C, 100°C and those sun dried and subsequently stored for one, three and six months were determined.

4.3 Results and Discussion

The dried samples were stored for one, three and six months and milled to access their quality. The main quality criterion used was head rice yield (HRY). Head rice yield was determined using equation 3.10. The results are presented below.

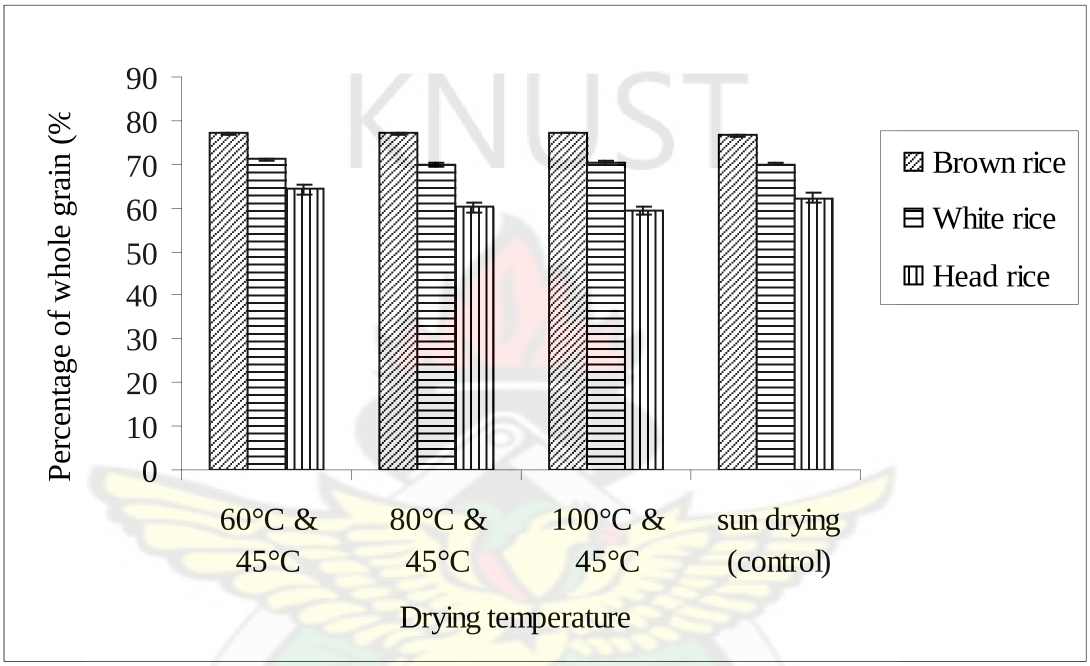

Figure 4.4 Comparison of milling quality and drying temperature for one month of storage using fluidised bed and fixed bed drying.
Bars represent standard error

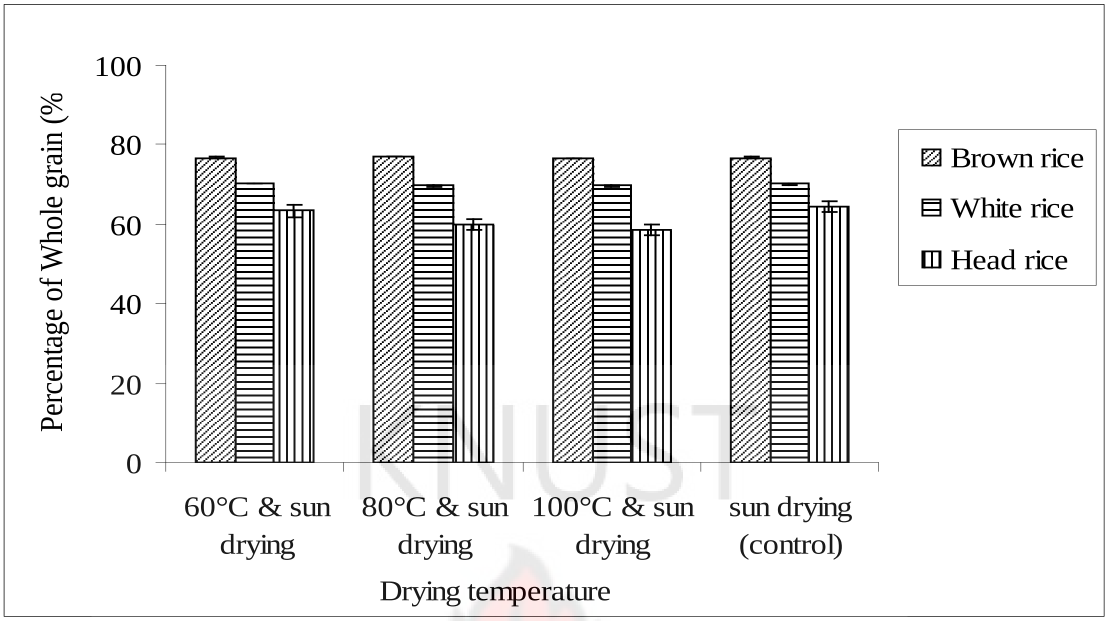

Figure 4.5 Comparison of milling quality and drying temperature for one month of storage using fluidised bed and sun drying
Bars represent standard error

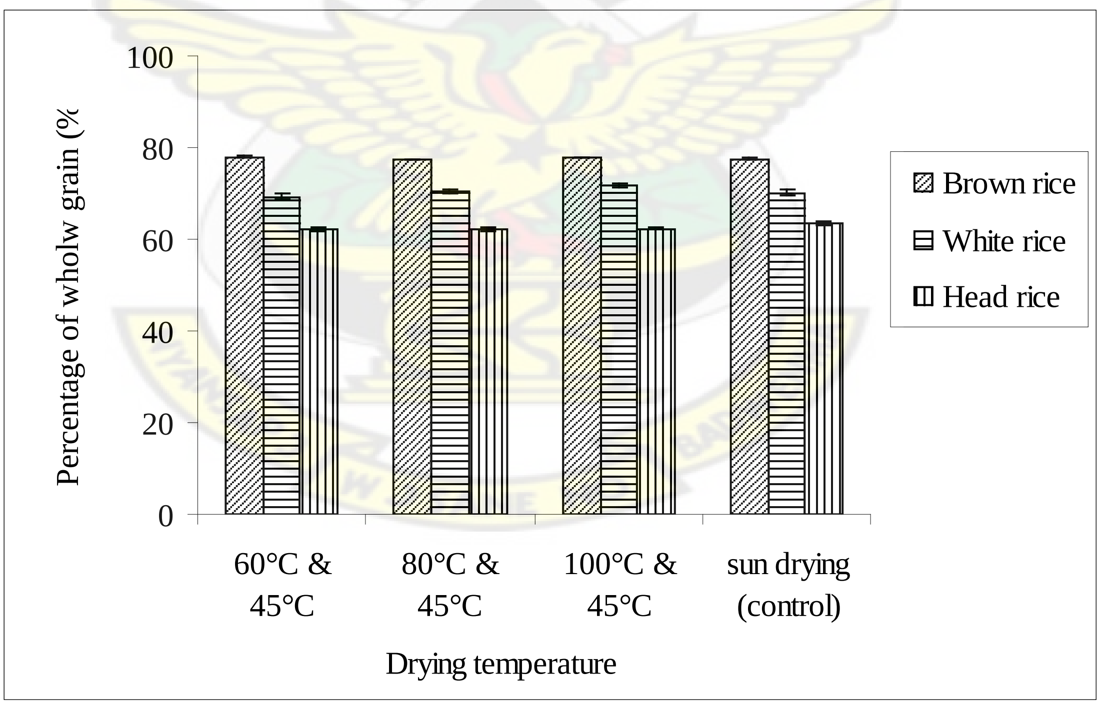

Figure 4.6 Comparison of milling quality and drying temperature for three months of storage using fluidised bed and fixed bed drying
Bars represent standard error

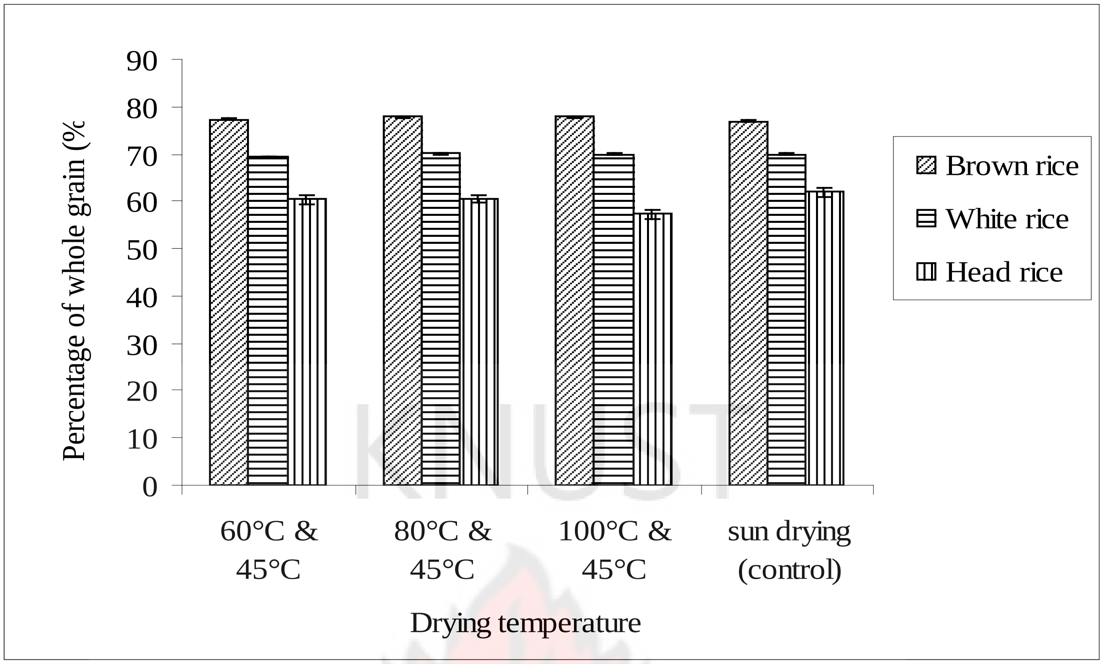

Figure 4.7 Comparison of milling quality and drying temperature for six months of storage using fluidised bed and fixed bed drying
Bars represent standard error

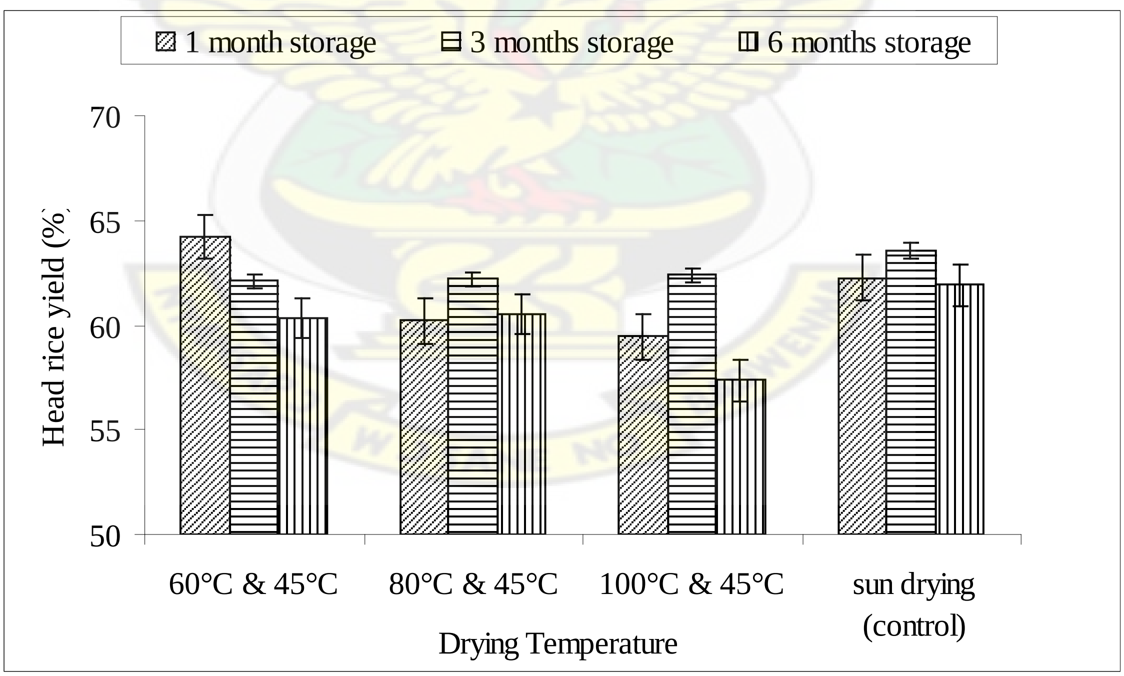

Figure 4.8 Comparison of head rice yield and the duration of storage
Bars represent standard error

From the results presented above in Figure 4.8 (for fluidised bed and fixed bed drying), as the drying temperature for the one month of storage increased from 60°C to100°C, the HRY reduced from 64.22% to 59.54%. When paddy was dried in the sun from the initial moisture content, it gave a better HRY of 62.27%. Drying at a lower temperature gave higher HRY. Drying at 60°C and subsequent storage indicated a reduction in HRY as the paddy was milled in the first, third and sixth months. This finding was contrary to what was expected. Milling during the first month of storage gave a better yield than storage for three and six months (Figure 4.8).

A noticeable marginal increase in HRY was observed when paddy was stored for three months as the temperature increased from 60°C to100°C. An increase in head rice is usually accompanied by a reduction in the number of fissured kernels (Iguaz *et al.*, 2006). The complete sun drying resulted in a higher HRY than the three temperatures. Figure 4.7 gives the results for six months of storage for 60°C, 80°C and 100°C. The HRY were 60.36%, 60.51% and 57.35% respectively. Drying at 80°C was the best in terms of HRY when dried paddy was stored for six months. The controlled sun drying again gave an indication of a better HRY (61.91%).

The second stage of drying where sun drying was employed indicated a reduction in HRY (63.29%, 60.06% and 58.37%) as the temperature increased from 60°C, 80°C and 100°C respectively (Figure 4.5). A good HRY was therefore achieved with the 60°C temperature whilst the lowest HRY came from the 100°C drying. This was expected as the drying temperature was higher.

Although sun drying yielded a better HRY of 64.25% (Figure 4.5), the advantage of hot-air drying is that it is not weather dependent. A disadvantage of sun drying is the stress involved and the extended time it takes to reach the storage moisture content. Again, the highest HRY was obtained from the three months of storage of the sun-dried samples. The lowest head yield was obtained from the 100°C drying. This is in line with the research carried out by Wongpornchai *et al*., 2004, when they worked on the effects of drying methods and storage time on the aroma and milling quality of rice. It was obvious in their study that drying paddy with hot air at high temperature (70°C) resulted in the lowest head rice yield.

Generally, the results in this study demonstrated that, the three months of storage had comparatively a better HRY for all the three temperatures (Figure 4.8). However, the single temperature which had the best HRY was 60°C, when it was stored for just one month and milled. The results suggest that, the duration of storage and temperature during drying had less effect on the quality of milled rice. Head rice yield of jasmine rice dried at 60°C, 80°C and 100°C and subsequent storage for one, three and six months were compared and the results showed that there was no significant difference ($p>0.05$) between the mean temperatures and months of storage. These findings are contrary to Ng *et al*., (2005), when they found that, high temperature (80°C) two-stage drying of 4cm bed had significantly lower crack percentage than those of 2 cm. They found that, there was significant difference in the head rice percentage.

4.4 Conclusions

After the storage and milling experiments carried out on jasmine rice, the HRY was calculated for all the samples milled. Based on the results and observations obtained, the following conclusions were made:

1. Drying at 60ºC gave a higher HRY than at 80ºC and 100ºC.
2. Generally, the three months of storage had a comparatively better HRY for all the three temperatures than the one and six months of storage. This was when fixed bed drying was employed at the second stage of drying.
3. The second stage of drying where sun drying was employed indicated a reduction in HRY as the temperature increased from 60°C, 80°C and 100°C.
4. The duration of storage and temperature at drying had less effect on the quality of milled rice.
5. Head rice yield of jasmine rice dried at 60°C, 80°C and 100°C and subsequent storage for one, three and six months were compared and the results showed that there was no significant difference ($p>0.05$) between the mean temperatures and months of storage.

CHAPTER FIVE

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATION

5.1 General Discussion

Rough rice is usually harvested at high moisture content and needs to be dried up to the desired storage moisture content of 14% wb or less. This is to allow for long storage and also to achieve better quality milling. A number of approaches have been adopted over the years to dry rough rice. The prominent among them is hot or heated air drying.

Paddy is dried from the initial moisture content up to the storage moisture content using one drying pass. A two-stage drying can also be employed, where paddy is rapidly dried in a fast rate dryer (such as a fluidised bed dryer) and then slowly dried in a low air temperature and low air velocity dryer (such as a static dryer). The two-stage drying is the concept that was used in this study.

Sun drying, a natural drying method is usually employed by most farmers in southern Ghana. Harvested paddy is usually spread on the ground and exposed to the effects of high humidity, sun and wind. The sun supplies the needed heat to evaporate the moisture around and within the grain kernels and the wind removes the evaporated moisture away. However, during unfavourable drying conditions such as rain or when there is high relative humidity in air, drying is impeded. There would be re-absorption of moisture during such periods. Sun drying is therefore not suitable for commercial rice production because it is weather dependent and labour intensive. Comparatively, it is fairly cheaper and sometimes gives better milling yields than heated air drying.

Artificial grain drying is not weather dependent. Large quantities of grain can be dried in any season. The two-stage drying is one of the artificial methods of grain drying.

5.1.1 Effects of drying on the quality of Jasmine rice

The first stage of drying where the fluidised bed was employed gave higher drying rates than the static and sun drying employed during the second stage of drying. This could be attributed to a number of reasons. First, the fast rate of drying could be due to the high temperatures (60ºC, 80ºC and 100ºC) employed during the drying phase. It could also be due to the suspension and the air flow rate that was experienced in the fluidised bed dryer. The other reason could be due to the initial high moisture of the paddy. When paddy was first dried using hot air, the breakage associated with high temperature drying was reduced since the drying exposure was very short (between 4 and 8 min). This is in agreement with Brown *et al*. (1979) and Weller et al. (1990), who also reported that the frequency of crack formation differed among grain lots and is affected by treatments such as grain initial moisture content and drying air temperature.

The second stage of drying in which the static bed dryer (at 45ºC) was used took relatively much longer time (more than 240 min) to dry the paddy from ≤19% wb to ≤14% wb. This stage was regarded as a tempering stage, so that the moisture would slowly migrate from the inner part of the seed to the outside part where it is evaporated by the air in the drying medium. There was a faster rate of drying when sun drying was used in the second stage of drying. This was more pronounced in the samples which were initially dried at 100ºC at the first stage. The drying constant, *k*, increased as the temperature was increased from 60ºC to 100ºC.

Using sun drying to dry grain from the initial moisture content it took about 630 min to dry up to ≤14%, while the two stage drying took a lesser time (about 240 min). This result suggests that the fluidised bed dryer would be better suited to reduce the moisture level of paddy to ≤19% and then subsequently dried using a slow dryer such as the static dryer or sun drying.

The Page equation gave a better prediction of the drying data since that had higher values of R^2, 0.96626 to 0.86235, and the Single Exponential model had lower R^2 values of 0.89123 to 0.62460. From the RME and RMSE values, the Page model described the drying data better since it had smaller values than that of the Single Exponential model.

5.1.2 Effect of drying on the milling quality of Jasmine rice

Rice is consumed as a whole grain. Therefore, the quality of the whole grain produced is of paramount importance to the consumer. The quantity and quality of grain left after milling is therefore essential to attract a good market for paddy. The HRY is therefore one of the main quality parameter used to assess the quality of milled rice.

The results from the milling experiments showed that drying at a temperature of 60ºC and storing for just one month would give a better HRY than storing for three or six months. A temperature of 80ºC and 100ºC during the first stage of drying however had an increased HRY as the storage time increased from one to six months, as expected. Of the one, three and six months of storage, the three months of storage had a better HRY. Storage for three months would be a better option for paddy before milling. Prolonged storage would tend to give a lower HRY.

Differences in HRY as a result of the mean temperatures were not significant ($p>0.05$). What it therefore means is that the different temperatures did not create a marked difference in the HRY of the milled rice. Drying in open air as a control gave a better HRY than the high temperature drying. This can be attributed to the low ambient temperatures and the slow rate of drying. Sun drying however took a much longer time to reach the required moisture content for prolonged storage and milling.

5.2 Conclusions

The results and observations in this study indicate that the fluidised bed dryer is suitable for quickly reducing the moisture content of high moisture paddy at harvest. Sun drying resulted in less cracking because the highest HRY was from sun drying. The following general conclusions were therefore made.

1. At the first stage of drying where a fluidised bed dryer was used, moisture reduction was rapid. It took about four to eight minutes to reduce the moisture to 18% wb and below. The drying time depended on the temperature during drying. Drying at 100ºC lasted for just about four minutes. The duration of drying increased as the temperature reduced to 60ºC.

2. It took comparatively more time to dry the paddy from the initial moisture content to the final storage moisture content with open air drying. This is seen as

a disadvantage of open air drying. Apart from the time spent on the drying phase, the paddy may also be exposed to unfavourable weather conditions such as rain, wind, high relative humidity, among others. It is, however good since the low drying temperature, resulted in less cracks during drying.

3. At the second stage of drying where a fixed bed dryer was used, the drying rate constant, *k*, increased from 0.08672/h to 0.139264/h when the Page equation was used to predict the moisture ratio as the temperature increased from 60ºC to 100ºC.
4. When the temperature of drying using the fluid bed drying was 60°C, it took about 270 min to dry to the storage moisture content using sun drying in the second stage. A temperature of 100°C in the first stage and sun drying in the second stage, took about 240 min. However, when paddy was dried in the sun, from the initial moisture content to the storage moisture content, it took about 630 min.
5. The Page model described the data better than the Single Exponential model. It had higher R^2 values of between 0.96626 to 0.86235 and lower values of RME and RMSE of 9.2127×10^{-4} and 2086.0×10^{-4} and 6.1185×10^{-4} and 1569.29×10^{-4} respectively.
6. Activation energy was calculated as 12.388×10^{-3} kJ/mol and 8.231×10^{-3} kJ/mol for fluidised and fixed bed, and fludised and sun drying respectively.
7. Drying at 60ºC gave a higher HRY than at 80ºC and 100ºC. Clearly, one can attribute this to the low drying temperature.
8. Generally, the three months of storage had a better HRY for all the three temperatures than the one or six months of storage. This was when fixed bed

drying was employed in the second stage of drying. The second stage of drying where sun drying was employed indicated a reduction in HRY as the temperature increased from 60°C, 80°C and 100°C.

9. Head rice yield of jasmine rice dried at 60°C, 80°C and 100°C and subsequent storage for one, three and six months were compared and the results showed that there was no significant difference ($p>0.05$) between the mean temperatures and months of storage. Therefore, the duration of storage and temperature during drying had less effect on the quality of milled rice.

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APPENDICES

APPENDIX A

DETERMINATION OF MOISTURE RATIO (MR)

Table 1: Experimental and calculated moisture ratio for 60°C fluidised bed and 45°C fixed bed drying.

Time (min)	Average MC wb (%)	MC db (%)	MR (Mi/Mo)	MR Page's model	MR Single exponential	Drying rate
0	22.440	28.932	1.000	1.000	0.838	0.000
2	21.001	26.584	0.919	0.896	0.835	1.174
4	20.033	25.051	0.866	0.871	0.833	0.767
6	19.344	23.984	0.829	0.854	0.830	0.534
8	18.814	23.173	0.801	0.840	0.828	0.405
28	18.247	22.319	0.771	0.768	0.803	0.427
48	17.775	21.618	0.747	0.729	0.778	0.351
68	17.296	20.913	0.723	0.701	0.755	0.353
88	16.775	20.156	0.697	0.679	0.732	0.378
108	16.341	19.532	0.675	0.660	0.709	0.312
128	15.943	18.967	0.656	0.645	0.688	0.283
148	15.578	18.453	0.638	0.631	0.667	0.257
168	15.191	17.912	0.619	0.618	0.647	0.271
188	14.930	17.551	0.607	0.607	0.627	0.180
208	14.592	17.085	0.591	0.597	0.608	0.233
228	14.216	16.571	0.573	0.587	0.590	0.257
248	14.038	16.331	0.564	0.578	0.572	0.120
268	13.974	16.244	0.561	0.570	0.554	0.044
288	13.904	16.149	0.558	0.562	0.537	0.047
308	13.832	16.053	0.555	0.555	0.521	0.048
328	13.596	15.735	0.544	0.548	0.505	0.159
			$MR_{exp,\,i}$ Σ=14.493	**$MR_{cal,\,i}$ Σ=14.496**	**$MR_{cal,\,i}$ Σ=14.457**	

Table 2: Experimental and calculated moisture ratio for 80°C fluidised bed and 45°C fixed bed drying.

Time (min)	Average MC wb (%)	MC db (%)	MR (Mi/Mo)	MR Page's model	MR Single exponential	Drying rate
0	22.440	28.932	1.000	1.000	0.815	0.000
1	21.134	26.797	0.926	0.886	0.813	1.068
2	20.171	25.267	0.873	0.862	0.812	0.765
3	19.242	23.827	0.824	0.846	0.810	0.720
4	18.677	22.966	0.794	0.833	0.809	0.430
5	17.884	21.778	0.753	0.823	0.808	0.594
25	17.369	21.020	0.727	0.732	0.779	0.379
45	16.888	20.320	0.702	0.691	0.751	0.350
65	16.357	19.556	0.676	0.662	0.724	0.382
85	15.878	18.875	0.652	0.640	0.698	0.340
105	15.426	18.240	0.630	0.622	0.673	0.318
125	14.976	17.614	0.609	0.607	0.649	0.313
145	14.574	17.060	0.590	0.594	0.626	0.277
165	14.205	16.557	0.572	0.582	0.603	1.000
185	13.841	16.064	0.555	0.571	0.582	0.247
205	14.031	16.322	0.564	0.561	0.561	-0.129
225	14.064	16.365	0.566	0.553	0.541	-0.022
245	13.971	16.240	0.561	0.544	0.521	0.063
265	13.835	16.056	0.555	0.537	0.503	0.092
			$MR_{exp, i}$ Σ=13.129	**$MR_{cal, i}$ Σ=13.147**	**$MR_{cal, i}$ Σ=13.077**	

Table 3: Experimental and calculated moisture ratio for 100°C fluidised bed and 45°C fixed bed drying.

Time (min)	Average MC wb (%)	MC db (%)	MR (Mi/Mo)	MR Page's model	MR Single exponential	Drying rate
0	22.440	28.932	1.000	1.000	0.835	0.000
1	21.002	26.586	0.919	0.870	0.834	1.173
2	19.622	24.413	0.844	0.846	0.832	1.087
3	18.240	22.310	0.771	0.830	0.831	1.052
4	17.735	21.558	0.745	0.818	0.791	0.376
24	17.335	20.970	0.725	0.725	0.750	0.294
44	16.898	20.334	0.703	0.686	0.711	0.318
64	16.471	19.719	0.682	0.660	0.673	0.307
84	16.049	19.118	0.661	0.640	0.638	0.301
104	15.636	18.533	0.641	0.624	0.605	0.292
124	15.273	18.026	0.623	0.610	0.573	0.254
144	14.938	17.561	0.607	0.598	0.543	0.233
164	14.606	17.105	0.591	0.587	0.514	0.228
184	14.295	16.680	0.577	0.578	0.835	0.213
204	14.079	16.385	0.566	0.569	0.834	0.147
224	13.792	15.999	0.553	0.561	0.832	0.193
244	13.466	15.561	0.538	0.554	0.831	0.219
264	13.392	15.462	0.534	0.547	0.791	0.049
			$MR_{exp, i}$ Σ=12.279	**$MR_{cal, i}$ Σ=12.305**	**$MR_{cal, i}$ Σ=12.235**	

Table 4: Experimental and calculated moisture ratio for 60°C fluidised bed and sun drying.

Time (min)	Average MC wb (%)	MC db (%)	MR (Mi/Mo)	MR Page's model	MR Single exponential	Drying rate
0	22.440	28.932	1.000	1.000	0.822	0.000
2	21.139	26.806	0.927	0.892	0.820	1.063
4	20.191	25.299	0.874	0.865	0.817	0.754
6	19.485	24.201	0.836	0.846	0.815	0.549
8	18.973	23.416	0.809	0.832	0.812	0.392
10	17.734	21.556	0.745	0.819	0.809	0.930
40	16.868	20.291	0.701	0.725	0.772	0.633
70	16.147	19.257	0.666	0.678	0.736	0.517
100	15.528	18.383	0.635	0.644	0.702	0.437
130	15.061	17.732	0.613	0.618	0.669	0.325
160	14.710	17.247	0.596	0.596	0.638	0.242
190	14.429	16.862	0.583	0.577	0.609	0.192
220	13.870	16.104	0.557	0.561	0.580	0.379
250	14.358	16.765	0.579	0.547	0.553	-0.331
280	14.124	16.448	0.568	0.534	0.528	0.159
310	13.780	15.982	0.552	0.522	0.503	0.233
			$MR_{exp, i}$ Σ=11.243	**$MR_{cal, i}$ Σ=11.256**	**$MR_{cal, i}$ Σ=11.186**	

Table 5: Experimental and calculated moisture ratio for 80°C fluidised bed and sun drying.

Time (min)	Average MC wb (%)	MC db (%)	MR (Mi/Mo)	MR Page's model	MR Single exponential	Drying rate
0	22.440	28.932	1.000	1.000	0.833	0.000
1	21.172	26.859	0.928	0.895	0.831	1.037
2	20.125	25.195	0.871	0.873	0.830	0.832
3	19.378	24.036	0.831	0.858	0.829	0.580
4	18.646	22.920	0.792	0.846	0.827	0.558
34	17.385	21.043	0.727	0.729	0.790	0.938
64	16.702	20.050	0.693	0.683	0.754	0.496
94	16.040	19.104	0.660	0.652	0.719	0.473
124	15.520	18.372	0.635	0.629	0.686	0.366
154	15.112	17.802	0.615	0.610	0.655	0.285
184	14.777	17.340	0.599	0.593	0.625	0.231
214	14.572	17.057	0.590	0.579	0.596	0.141
244	14.151	16.484	0.570	0.567	0.569	0.287
274	13.676	15.843	0.548	0.556	0.543	0.320
304	13.770	15.969	0.552	0.545	0.518	-0.063
334	13.326	15.376	0.531	0.536	0.495	0.297
			$MR_{exp, i}$ Σ=11.143	**$MR_{cal, i}$ Σ=11.151**	**$MR_{cal, i}$ Σ=11.101**	

Table 6: Experimental and calculated moisture ratio for 100°C fluidised bed and sun drying.

Time (min)	Average MC wb (%)	MC db (%)	MR (Mi/Mo)	MR Page's model	MR Single exponential	Drying rate
0	22.440	28.932	1.000	1.000	0.835	0.000
1	20.948	26.499	0.916	0.884	0.834	1.217
2	19.778	24.655	0.852	0.861	0.832	0.922
3	18.398	22.546	0.779	0.846	0.831	1.055
30	17.493	21.201	0.733	0.727	0.791	0.672
60	16.717	20.072	0.694	0.680	0.750	0.565
90	16.035	19.098	0.660	0.649	0.711	0.487
120	15.467	18.297	0.632	0.626	0.673	0.400
150	15.065	17.737	0.613	0.608	0.638	0.280
180	14.608	17.107	0.591	0.592	0.605	0.315
210	14.191	16.538	0.572	0.579	0.573	0.285
240	13.998	16.277	0.563	0.567	0.543	0.131
270	13.923	16.176	0.559	0.557	0.514	0.050
			$MR_{exp, i}$ Σ=9.164	**$MR_{cal, i}$ Σ=9.176**	**$MR_{cal, i}$ Σ=9.130**	

Table 7: Experimental and calculated moisture ratio for complete sun drying (control).

Time (min)	Average MC wb (%)	MC db (%)	MR (Mi/Mo)	MR Page's model	MR Single exponential	Drying rate
0	22.440	28.932	1.000	1.000	0.878	0.000
30	21.435	27.283	0.943	0.930	0.864	0.825
60	20.763	26.204	0.906	0.893	0.850	0.539
90	20.350	25.550	0.883	0.864	0.836	0.327
120	19.511	24.241	0.838	0.840	0.822	0.654
150	18.902	23.308	0.806	0.818	0.809	0.467
180	18.384	22.525	0.779	0.798	0.796	0.391
210	17.794	21.645	0.748	0.780	0.783	0.440
240	17.298	20.917	0.723	0.763	0.770	0.364
270	16.757	20.131	0.696	0.748	0.757	0.393
300	16.414	19.638	0.679	0.733	0.745	0.247
330	16.121	19.219	0.664	0.719	0.733	0.209
360	15.944	18.969	0.656	0.706	0.721	0.125
390	15.762	18.712	0.647	0.693	0.709	0.129
420	15.558	18.425	0.637	0.681	0.697	0.144
450	15.312	18.081	0.625	0.670	0.686	0.172
480	15.047	17.712	0.612	0.659	0.675	0.185
510	14.707	17.243	0.596	0.648	0.664	0.235
540	14.421	16.851	0.582	0.638	0.653	0.196
570	14.105	16.421	0.568	0.628	0.642	0.215
600	13.863	16.095	0.556	0.619	0.632	0.163
630	13.609	15.753	0.544	0.610	0.621	0.171
			$MR_{exp, i}$ Σ=14.687	**$MR_{cal, i}$ Σ=16.440**	**$MR_{cal, i}$ Σ=16.341**	

APPENDIX B

DRYING PARAMETERS DETERMINED

Table 8: 60°C fluidised bed and 45°C fixed bed drying.

Parameter	Page's Model	Single Exponential Model
Equation of the graph	Y=0.334338X-2.44506	Y=-0.001542X-.176785
Coefficient of determination, R^2	0.96626	0.89123
Drying constant rate, *k*	0.08672/h	0.00154/h
Constant, *n*	0.334338	-
Diffusion coefficient, *a*	-	0.8380
Root Mean Error, RME	0.000921269	0.011905153
Root Mean Square Error, RMSE	0.000611854	0.007907

Table 9: 80°C fluidised bed and 45°C fixed bed drying.

Parameter	Page's Model	Single Exponential Model
Equation of the graph	Y=0.292969X-2.109129	Y=-0.001822X-.204680
Coefficient of determination, R^2	0.91890	0.80964
Drying constant rate, *k*	0.121344/h	0.001822/h
Constant, *n*	0.292969	-
Diffusion coefficient, *a*	-	0.8149
Root Mean Error, RME	0.00701	0.020791
Root Mean Square Error, RMSE	0.004011	0.011898

Table 10: 100°C fluidised bed and 45°C fixed bed drying.

Parameter	Page's Model	Single Exponential Model
Equation of the graph	Y=0.262837X-1.971386	Y=-0.001812X-.209627
Coefficient of determination, R^2	0.87801	0.83434
Drying constant rate, *k*	0.139264/h	0.001812/h
Constant, *n*	0.262837	-
Diffusion coefficient, *a*	-	0.8109
Root Mean Error, RME	0.011884399	0.019694
Root Mean Square Error, RMSE	0.006191	0.010259

Table 11: 60°C fluidised bed and sun drying.

Parameter	Page's Model	Single Exponential Model
Equation of the graph	Y=0.344377X-2.406438	Y=-0.001584X-.195560
Coefficient of determination, R^2	0.92899	0.78307
Drying constant rate, *k*	0.09014/h	0.00158/h
Constant, *n*	0.344377	-
Diffusion coefficient, *a*	-	0.8224
Root Mean Error, RME	0.005538787	0.031301607
Root Mean Square Error, RMSE	0.003269227	0.014077

Table 12: 80°C fluidised bed and sun drying.

Parameter	Page's Model	Single Exponential Model
Equation of the graph	Y=0.297521X-2.201599	Y=-0.001559X-.183118
Coefficient of determination, R^2	0.94365	0.84885
Drying constant rate, *k*	0.11063/h	0.00156/h
Constant, *n*	0.297521	-
Diffusion coefficient, *a*	-	0.8327
Root Mean Error, RME	0.0036508	0.0232935
Root Mean Square Error, RMSE	0.002136	0.010382

Table 13: 100°C fluidised bed and sun drying.

Parameter	Page's Model	Single Exponential Model
Equation of the graph	Y=0.277989X-2.090688	Y=-0.001796X-.180029
Coefficient of determination, R^2	0.92437	0.82723
Drying constant rate, *k*	0.12360/h	0.00180/h
Constant, *n*	0.277989	-
Diffusion coefficient, *a*	-	0.8352
Root Mean Error, RME	0.0103452	0.0287869
Root Mean Square Error, RMSE	0.003418173	0.009511

Table 14: Complete sun drying (control).

Parameter	Page's Model	Single Exponential Model
Equation of the graph	Y=0.628176X-4.752434	Y=-0.000549X-.129901
Coefficient of determination, R^2	0.86235	0.62460
Drying constant rate, *k*	0.008630663/h	0.00055/h
Constant, *n*	0.628176	-
Diffusion coefficient, *a*	-	0.8782
Root Mean Error, RME	0.20859676	-0.189500468
Root Mean Square Error, RMSE	0.156929	0.139429

APPENDIX C

DETERMINATION OF HEAD RICE YIELD (HRY)

$$\text{Head Rice Yield} = \frac{\text{weight of head rice}}{\text{total grain weight}} \times 100\% \quad (3.10)$$

Table 15: Milling Experimental Data for 60°C fluidised bed and 45°C fixed bed drying.

One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	386.00	385.00	77.20	77.00	77.10
White rice	357.50	354.40	71.50	70.88	71.19
HRY	320.40	321.80	64.08	64.36	64.22

	Three months of storage		Six Months of storage	
Type	Weight (g)	Percentage (%)	Weight (g)	Percentage (%)
Rough rice	500.00	100.00	500.00	100.00
Brown rice	390.00	78.00	386.47	77.29
White rice	346.44	69.29	347.3	69.46
HRY	310.53	62.11	301.78	60.36

Table 16: Milling Experimental Data for 80°C fluidised bed and 45°C fixed bed drying.

One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	384.80	385.00	76.96	77.00	76.98
White rice	348.10	350.30	69.62	70.06	69.84
HRY	300.00	302.20	60.00	60.44	60.22

	Three months of storage		Six Months of storage	
Type	Weight (g)	Percentage (%)	Weight (g)	Percentage (%)
Rough rice	500.00	100.00	500.00	100.00
Brown rice	387.40	77.48	389.05	77.81
White rice	352.51	70.50	350.79	70.16
HRY	311.00	62.20	302.54	60.51

Table 17: Milling Experimental Data for 100°C fluidised bed and 45°C fixed bed drying.

One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	385.40	386.00	77.08	77.20	77.14
White rice	348.30	356.00	69.66	71.20	70.43
HRY	295.20	299.30	59.04	59.86	59.45

	Three months of storage		**Six Months of storage**	
Type	Weight (g)	Percentage (%)	Weight (g)	Percentage (%)
Rough rice	500.00	100.00	500.00	100.00
Brown rice	388.93	77.79	389.49	77.90
White rice	358.58	71.72	349.88	69.98
HRY	311.87	62.37	286.74	57.35

Table 18: Milling Experimental Data for complete sun drying (control) for fluidised be and fixed bed drying.

One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	382.80	382.90	76.56	76.58	76.57
White rice	352.50	348.30	70.50	69.66	70.08
HRY	312.40	310.30	62.48	62.06	62.27

	Three months of storage		**Six Months of storage**	
Type	Weight (g)	Percentage (%)	Weight (g)	Percentage (%)
Rough rice	500.00	100.00	500.00	100.00
Brown rice	387.77	77.55	384.73	76.95
White rice	351.01	70.20	349.94	69.99
HRY	317.76	63.55	309.53	61.91

Table 19: Milling Experimental Data for 60°C fluidised bed and sun drying. One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	384.00	383.50	76.80	76.70	76.75
White rice	351.90	351.40	70.38	70.28	70.33
HRY	316.50	316.40	63.30	63.28	63.29

Table 20: Milling Experimental Data for 80°C fluidised bed and sun drying. One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	383.80	386.50	76.76	77.30	77.03
White rice	345.70	351.70	69.14	70.34	69.74
HRY	295.00	305.60	59.00	61.12	60.06

Table 21: Milling Experimental Data for 100°C fluidised bed and sun drying. One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	383.10	383.00	76.62	76.60	76.61
White rice	346.80	349.30	69.36	69.86	69.61
HRY	292.30	291.40	58.46	58.28	58.37

Table 22: Milling Experimental Data for complete sun drying (control) for fluidised bed and sun drying. One month of storage

Type	Weight (g)		Percentage (%)		Average %
	1	2	1	2	
Rough rice	500.00	500.00	100.00	100.00	100.00
Brown rice	383.10	384.80	76.62	76.96	76.79
White rice	350.30	350.70	70.06	70.14	70.10
HRY	318.50	324.00	63.70	64.80	64.25

APPENDIX D

FORMULAE AND CALCULATIONS

Initial Moisture Content determination

$$\text{MC wb} = \frac{\text{initial weight} - \text{final weight}}{\text{initial weight}} \times 100\% \qquad (3.1)$$

where

MC wb = moisture content (wet basis).

Container	Weight of paddy before drying (g)	Weight of paddy before drying (g)
1	15	11.63
2	15	11.66
3	15	11.63
4	15	11.62

$$MC_1 = \frac{15 - 11.63}{15} \times 100\% = 22.47\%$$

$$MC_2 = \frac{15 - 11.66}{15} \times 100\% = 22.27\%$$

$$MC_3 = \frac{15 - 11.63}{15} \times 100\% = 22.47\%$$

$$MC_4 = \frac{15 - 11.62}{15} \times 100\% = 22.53\%$$

$$\text{Average moisture content } = \frac{(22.47 + 22.27 + 22.47 + 22.53)}{4} = 22.44\%$$

Therefore, initial moisture content, $MC_{wb.}$ = 22.44%

But, initial moisture content, $MC_{db.}$= $= \frac{MC_{wb}}{100 - MC_{wb}} \times 100\%$

where

$MC_{db.}$ = moisture content (dry basis).

$$MC_{db.} = = \frac{22.44}{100 - 22.44} \times 100\% = 28.93\%$$

- Determination of Moisture Ratio (MR)

  Formula for calculating Moisture Ratio

$$MR = \frac{M_i - M_e}{M_o - M_e} \text{...} (3.3)$$

where

MR = Moisture Ratio (dimentionless)
M_i = Moisture content (%db) at any time
M_e = Equilibrium Moisture Conten (%db)
M_o = Initial Moisture Content (%db)

Equation 3.5 was simplified to give equation.

$$MR = \frac{M_i}{M_o} \text{...} (3.4)$$

- **Determination of drying parameters**
  - Page's equation

$$MR = \exp(-kt^n)\ldots\ldots(2.3)$$

The equation can be transformed as follows:

$$-\ln(MR) = kt^n$$

$$\therefore \ln(-\ln(MR)) = \ln k + n\ln t\ldots\ldots(3.5)$$

Equation (3.5) is in the form of a straight line the relationship is as follows:

$y = \ln(-\ln MR)) = MR,$

$m = n,$

$x = \ln t$ and

$c = \ln k.$

Equation (3.5) can therefore be written as:

$$MR = \ln k + n\ln t\ldots\ldots(3.6)$$

  - Single exponential (Henderson and Pabis) equation

The equation is expressed as:

$$MR = a\ \exp(-kt)\ldots\ldots(2.6)$$

It can also be simplified into the form;

$$\ln MR = \ln a - kt\ldots\ldots(3.7)$$

The equation above is also in the form of a straight line and they relate as follows:

$y = \ln MR,$

$m = -k,$

$x = t$ and

$c = \ln a.$

- root mean error (RME)

The RME was calculated using equation 3.8.

$$RME = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|\left(MR_{\exp,i} - MR_{cal,i}\right)\right|}{MR_{\exp,i}} \text{.......................................}(3.8).$$

where

N = number of observations

$MR_{\exp,i}$ = experimental moisture ratio at i^{th} observation

$MR_{cal,i}$ = calculated moisture ratio at i^{th} observation

- root mean square error (RMSE)

Equation 3.9 was applied to calculate RMSE.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{cal,i} - MR_{\exp,i}\right)}{N}} \text{.......................................}(3.9),$$

where

N = number of observations

$MR_{\exp,i}$ = experimental moisture ratio at *ith* observation

$MR_{cal,i}$ = calculated moisture ratio at *ith* observation

Application to MR, pages equation

- 60°C fluidised bed and 45°C fixed bed drying

$$RME = \frac{100}{21}\frac{\left|\left(14.49278 - 14.49558\right)\right|}{14.49278}$$

$$RME = 9.21269 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{\left|\left(14.9558 - 14.49278\right)\right|}{21}}$$

$$RMSE = 6.11854 \times 10^{-4}$$

- 80°C fluidised bed and 45°C fixed bed drying

$$RME = \frac{100}{19}\frac{|(13.12915 - 13.14663)|}{13.12915}$$
$$RME = 70.1 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(13.14663 - 13.12915)|}{19}}$$
$$RMSE = 40.11 \times 10^{-4}$$

- 100°C fluidised bed and 45°C fixed bed drying

$$RME = \frac{100}{18}\frac{|(12.27869 - 12.30495)|}{12.27869}$$
$$RME = 118.84399 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(12.30495 - 12.27869)|}{18}}$$
$$RMSE = 61.191 \times 10^{-4}$$

- 60°C fluidised bed and sun drying

$$RME = \frac{100}{16}\frac{|(11.24271 - 11.25579)|}{11.24271}$$
$$RME = 55.38787 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(11.25579 - 11.24271)|}{16}}$$
$$RMSE = 32.69227 \times 10^{-4}$$

- 80°C fluidised bed and sun drying

$$RME = \frac{100}{18}\frac{|(11.14257 - 11.15111)|}{11.14257}$$
$$RME = 36.508 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(11.15111 - 11.14257)|}{18}}$$
$$RMSE = 21.36 \times 10^{-4}$$

- 100°C fluidised bed and sun drying

$$RME = \frac{100}{13}\frac{|(9.16395 - 9.17627)|}{9.16395}$$
$$RME = 103.52 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(9.17627 - 9.16395)|}{13}}$$
$$RMSE = 34.18173 \times 10^{-4}$$

- Sun drying (control)

$$RME = \frac{100}{22}\frac{|(15.68673 - 16.43934)|}{15.68673}$$
$$RME = 2085.9676 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(16.43934 - 15.68673)|}{22}}$$
$$RMSE = 1569.29 \times 10^{-4}$$

Application to MR, Single exponential equation

- 60°C fluidised bed and 45°C fixed bed drying

$$RME = \frac{100}{21}\frac{|(14.49278 - 14.45655)|}{14.49278}$$
$$RME = 119.05153 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(14.45655 - 14.49278)|}{21}}$$
$$RMSE = 79.07 \times 10^{-4}$$

- 80°C fluidised bed and 45°C fixed bed drying

$$RME = \frac{100}{19}\frac{|(13.12915 - 13.07728)|}{13.12915}$$
$$RME = 207.91 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(13.07728 - 13.12915)|}{19}}$$
$$RMSE = 118.98 \times 10^{-4}$$

- 100°C fluidised bed and 45°C fixed bed drying

$$RME = \frac{100}{18}\frac{|(12.27869 - 12.23516)|}{12.27869}$$
$$RME = 196.94 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(12.23516 - 12.27869)|}{18}}$$
$$RMSE = 102.59 \times 10^{-4}$$

- 60°C fluidised bed and sun drying

$$RME = \frac{100}{16}\frac{|(11.24271 - 11.18641)|}{11.24271}$$
$$RME = 313.01607 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(11.18641 - 11.24271)|}{16}}$$
$$RMSE = 140.77 \times 10^{-4}$$

- 80°C fluidised bed and sun drying

$$RME = \frac{100}{18}\frac{|(11.14257 - 11.10104)|}{11.14257}$$
$$RME = 232.935 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(11.10104 - 11.14257)|}{18}}$$
$$RMSE = 103.82 \times 10^{-4}$$

- 100°C fluidised bed and sun drying

$$RME = \frac{100}{13}\frac{|(9.16395 - 9.12966)|}{9.16395}$$
$$RME = 287.869.6444 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{|(9.12966 - 9.16395)|}{13}}$$
$$RMSE = 95.11 \times 10^{-4}$$

- Sun drying (control)

$$RME = \frac{100}{22}\frac{\left|(15.68673 - 16.34071)\right|}{15.68673}$$

$$RME = 1895.00468 \times 10^{-4}$$

$$RMSE = \sqrt{\frac{\left|(16.34071 - 15.68673)\right|}{22}}$$

$$RMSE = 1394.29 \times 10^{-4}$$

APPENDIX E

ANOVA TABLES

Anova: Single Factor **TEMPERATURES**

SUMMARY

Groups	Count	Sum	Average	Variance
60°C & 45°C	3	186.68	62.23	3.74
80°C & 45°C	3	182.93	60.98	1.14
100°C & 45°C	3	179.17	59.72	6.37
sun drying (control)	3	187.73	62.58	0.75

ANOVA

Source of Variation	SS	df	MS	F	**P-value**	F crit
Between Temperatures	15.16	3	5.05	1.68	**0.25**	4.07
Within Temperatures	24.01	8	3.00			
Total	**39.18**	**11**				

Anova: Single Factor **MONTHS OF STORAGE**

SUMMARY

Groups	Count	Sum	Average	Variance
1 Month	4	246.16	61.54	4.61
3 Months	4	250.23	62.56	0.45
6 Months	4	240.12	60.03	3.68

ANOVA

Source of Variation	SS	df	MS	F	**P-value**	F crit
Between Months	12.95	2	6.47	2.22	**0.16**	4.26
Within Months	26.23	9	2.91			
Total	**39.18**	**11**				