MODELING OF THIN LAYER DRYING CHARACTERISTICS OF GROUNDNUT SEEDS (*ARACHIS HYPOGEA*)

BY

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TO

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CERTIFICATION

This is to certify that this project work "Modelling of the thin layer drying characteristics of Groundnut seeds" was done by PACIFINE C.OBUMSELI in the Department of Agricultural and Bio Resources Engineering, Federal University of Technology Owerri

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DEDICATION

This workis dedicated specially to my faithful God for giving me the grace to carry out this project work

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ABSTRACT

Groundnut or Peanut is a legume crop with high nutritive value. Drying of groundnut is necessary in order to reduce the moisture content to a safe storage level and also increase the shelf life. Five thin layer drying models were fitted into the drying curve also the effective moisture diffusivity for groundnut seeds were calculated. Groundnut seeds with an Initial Moisture Content 67% (db) were dried to a safe moisture content of about 14% in a conventional tray dryer at temperatures of 45^{o}C, 55^{o}C, 65^{o}C, and air velocities of 0.6m/s, 1.0m/s and 1.5m/s .The effective moisture diffusivity was evaluated using Fick's second law and the dependence of moisture diffusivity on temperature was described by Arrhenius type equation. Comparisons of the drying rate models showed high coefficient of determination for Page model, two-term model, followed by Logarithmic, Henderson and Pabis model, and then the Newton Model of which has high error and low coefficient of determination.

The Model equation is MR = $\exp^{(-0.00119t)\ 1.43}$

Keywords: Groundnut, drying, models, Safe Moisture Content

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND OF STUDY

The groundnut (Arachis hypogea) is a legume crop grown mainly for its edible seeds. It is widely grown in the tropics and subtropics, being important to both small and large commercial producers. It is classified as both a grain legume and, because of its high oil content, an oil crop. (Seijo *et al*., 2007).As a legume, the peanut belongs to the botanical family Fabaceae; this is also known as Leguminosae, and commonly known as the *bean,* or *pea,* family.It is an annualherbaceous plant growing from 30 to about 50 cm (1.0 to 1.6 ft) tall. The leaves are opposite, pinnate with four leaflets (two opposite pairs; no terminal leaflet); each leaflet is 1 to 7 cm (⅜ to 2¾ in) long and 1 to 3 cm (⅜ to 1 inch) across.The flowers are of typicalpeaflower in shape, 2 to 4 cm (0.8 to 1.6 in) (¾ to 1½ in) across, yellow with reddish veining. The specific name is Hypogaea means "under the earth". After pollination, the flower stalk elongates, causing it to bend until the ovary touches the ground. (Seijo *et al*., 2007). Continued stalk growth then pushes the ovary underground where the mature fruit develops into a legume pod, the peanut – a classical example of geocarpy meaning production of fruits underground.(Seijo *et al*., 2007).

Groundnut Pods are 3 to 7 cm (1.2 to 2.8 in) long, containing 1 to 4 seeds. Because in botanical terms, "nut" specifically refers to indehiscent fruit, the peanut is not technically a nut, but rather a legume. (Adejumo *et al.,* 2005).

Groundnut is regarded as one of the most important protein-rich crops and it occupies the fifth position as oilseed crop globally after soybean, cottonseed, rape seed, and sunflower seed (El- Sayed*et al.,* 2001). It is grown as annual crop on about 19million hectares of land in tropical regions and the warmer areas of temperate regions of the world (Adejumo*et al.,* 2005).

Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. It is also one of the methods of food preservation, which provides longer shelf-life, lighter weight for transportation and smaller space for storage.

Seed **moisture content** is one of the factors which determine whether or not seed can be stored safely without loss of germination and vigor. When **moisture content** is too high the seed may heat and various moulds can grow. (FAO. 1993) Therefore it is absolutely vital to ensure that harvested seed is at a safe**moisture content** before putting it into store. A seed crop is often harvested when the seed **moisture content** is higher than desirable for safe storage. Safe seed **moisture content**s vary with crop species, but generally 14% or less is considered satisfactory for short term storage. (FAO. 1993)

Most high moisture seeds can be preserved for propagation purposes if properly dried. Seeds are susceptible to drying injury in several ways since they are sensitive to **high temperature**s, depending on the species. They may also be injured by drying too rapidly or by over drying. To obtain a good dryer performance, seed **moisture content**, depth of seed in bin, air temperature and air volume must be controlled. (Nagim *et al.*, 2004)

The major objective of drying food products is the reduction of moisture content to a level which allows safe storage over an extended period (Doymaz, 2006). Incidentally, drying is not only an energy intensive process but also a complex phenomenon, in which energy is used to provide heat and mass transfer in most cases. This has invoked several studies on energy consumption in industrial drying operations, which were reported as ranging from 10-15% to 20-25% of the total energy consumption (Mujumdar*et al.,* 2004; Chua*et al.,* 2003).

Most food crops contain more than 80% water at harvest and are therefore highly perishable if stored or left long in that state. Water loss and decay account for most of their losses, which are estimated to be more than 30% in the developing countries due to inadequate handling, transportation and storage (Kaya *et al.,* 2007). These losses cause serious gaps in the provision of the essential nutrients, vitamins and minerals which they supply to human diet. Farm crops in Nigeria are used for human and animal consumption while the remaining are used for subsequent propagation. Preservation of the qualities of the harvested crops before their time of use is very important .

Moisture control in post harvest processes involves reduction of moisture content to a level which becomes unfavourable for microorganisms and enzymes responsible for spoilage of foods and biomaterials. In a nutshell, freshly harvested crops have relatively high moisture content which has to be reduced to a desirable level, usually below 12% (wb) for most grains and slightly above that for fruits and vegetables before they can be safely stored. (FAO. 1993)

Modern agriculture has brought about the handling and processing of plant and animal materials by various means ranging from mechanical, thermal, electrical, optical, to even sonic techniques. The ever increasing importance of agricultural products together with the complexity of modern technology for their production, processing and storage need a better knowledge of their engineering properties so that machines, processes and handling operations can be designed for maximum efficiency and the highest quality of the final end products .

Successful drying depends on:

- enough heat to draw out moisture, without cooking the grain,
- dry air to absorb the released moisture; and
- adequate air circulation to carry of the moisture.

(Raghavan and Sosle 2007).

When drying grains, the key factor is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavor, texture and colour of the grain. If the temperature is too low in the beginning, microorganisms may grow before the grain is adequately dried

Therefore, reasons for crop drying can be summarized to include the following:

a) To reduce incidence of enzyme attacks, insect and fungal infestations, stain and decay
b) To enhance the mechanical properties of the crops, such as strength, hardness, and thermal insulation in order to stand mechanical impact of handling and processing systems.
c) To reduce the weight and volume of the crops, thereby resulting in reduction of transportation cost and storage space.

Logically, therefore, drying of agricultural products is an important operation to get the desirable condition for their consumption; marketing and storage.

1.2 STATEMENT OF PROBLEM

Knowledge of the drying modelsof a crop is very important in the design of the drying equipment.No drying equation has been found to be perfectly suitable for all crops, though a good number of works have been carried out in this area of postharvest operation on various crops and their varieties. Poor storage of peanuts can lead to an infection by the moldfungusAspergillusflavus, releasing the toxic and highly carcinogenic substance aflatoxin.The studies in this work attempted to analyze suitable drying models for the groundnut seeds and the influence of the drying conditions on various parameters of the drying process.

1.3OBJECTIVES OF STUDY

The main objective of this study is to characterize, model and simulate the drying process of groundnut seeds.

The specific objectives include:

i. To experimentally investigate drying characteristics of groundnut such as drying rate and drying constants
ii. To develop appropriate models for simulating drying kinetics of groundnut seeds;
iii. To determine the effects of thermal properties of air (such temperature, density) on the drying parameters of groundnut seeds.
iv. To determine the effects of properties of air on the drying parameters of groundnut seeds

1.4 SCOPE

The groundnut used(*Kerstingiella geocarpa Harms Specie*) washarvested from a farm in Anam, Anambra West Local Government Area of Anambra State in the

South Eastern part of Nigeria.Modelingwas based on using some set of equations to describe the system as accurately as possible. Five thin layer drying models were Page model, Newton Model, Two -Term model, Henderson and Pabis model, and Logarithmic model. The drying air velocities were; 0.6m/s, 1.0m/s and 1.5m/s and the drying air temperatures were within the range of 45^{o}C to 65^{o}C.

1.5 LIMITATIONS

This analysis was carried out using only one specie of groundnut(*Kerstingiella geocarpa Harms Specie*). The result may vary for other speices. Also the analysis was carried out during rainy season, this may affect the initial moisture content of the harvested groundnut

1.6SIGNIFICANCE OF STUDY

Information on the drying characteristics of a crop is necessary for optimal design and operation of dryers as well as properly meeting the optimal storage conditions for such crops. While the number of drying models has steadily increased over the years, there is no clear consensus model that has the desired accuracy and the simplicity required for efficient simulation in a broad range of applications to low temperature and natural air drying equipment specific to most Nigerian crops.

CHAPTER TWO

LITERATURE REVIEW

2.1 OVERVIEW OF THE GROUNDNUT CROP

Groundnut (*Arachis hypogea*) is widely grown in the tropics and subtropics of the world. (Seijo *et al.*,2007). If this produce is not well managed and preserved, it will suffer big loss and underutilization. Hence there is need to dry it in order to reduce loss and enhance processing.

The groundnut is an amphidiploid or allotetraploid, meaning that it has two sets of chromosomes from two different species, thought to be*A. duranensis* and *A. ipaensis.* These probably combined in the wild to form the tetraploid species A. monticola, which gave rise to the domesticated peanut. (Nigam *et al.,* 2004)

Pollinated Peanut pod stalks in auxiliary clusters above ground. The stalk at the base of the ovary, called the pedicel, elongates rapidly, and turns downward to bury the fruits several inches in the ground, where they complete their development (Fig 2.1)

Fig 2.1: Sprouted groundnut(Seijo *et al*., 2007)

The entire plant, including most of the roots, is removed from the soil during harvesting (fig 2.2).The fruits have wrinkled shells that are constricted between pairs of the one to four (usually two) seeds per pod.(fig 2. 3)

Fig2.2 : Harvested groundnut(Seijo *et al*., 2007)

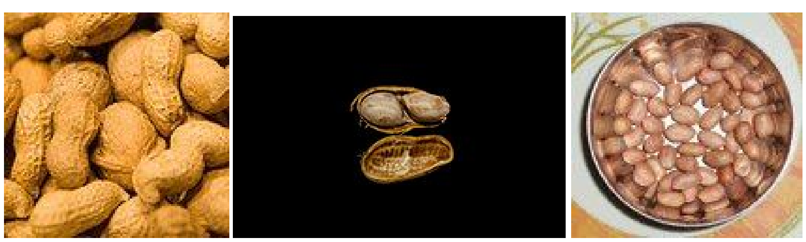


Fig 2.3Groundnuts seeds and pods(Nigam *et al*., 2004)

Peanuts are particularly susceptible to contamination during growth and storage. Poor storage of peanuts can lead to an infection, releasing the toxic and highly carcinogenic substance aflatoxin. The aflatoxin-producing molds exist throughout the peanut growing areas and may produce aflatoxin in peanuts when conditions are favorable to fungal growth. Drying will reduce this fungal growth and their rate of infestation. (FAOSTAT 2014)

2.2 SOME PHYSICAL AND CHEMCALCOMPOSITION OF GROUNDNUT

The basic composition of groundnut per 100 g of nuts is:

Water - 1.55 g

Carbohydrates - 21.51 g

Fiber - 8.0 g

Lipids (Fats) - 49.66 g

Proteins - 23.68 g

Energy (Total Calories) - 2448 kJ (585 kCal) (USDA 2011),

The sub composition of the above categories under every major molecule such as different minerals, vitamins, amino acids present in proteins, lipids comprising of various saturated and unsaturated fatty acids, carbohydrates comprising of poly-saccharides in the form of starch, organic acids, and purines, present in peanuts are shown in Table 2.1

TABLE 2.1: SUB COMPOSITION OF GROUNDNUT NUTRIENTS

AMINO ACIDSVITAMINS			
Type	Weight (g)*	Type	Weight (g)*
Tryptophan	0.230	Thiamin	0.438 × 10–3
Threonine	0.811	Riboflavin	0.098 × 10–3
Isoleucine	0.833	Niacin	13.525 × 10–3
Leucine	1.535	Pantothenic acid	1.395 × 10–3
Lysine	0.850	B6	0.256 × 10–3

Methioione	0.291	Folate	1450 × 10–6
Cysteine	0.304	E**	6.93 × 10–3
Phenylalanine	1.227	Choline	55.3 × 10–3
Tyrosine	0.963	**MINERALS**	
Valine	0.993	Calcium	54 × 10–3
Arginine	2.832	Iron	2.26 × 10–3
Histidine	0.599	Magnesium	176 × 10–3
Alanine	0.941	Phosphorous	358 × 10–3
Aspartic acid	2.888	Potassium	658 × 10–3
Glutamic acid	4.949	Sodium	6 × 10–3
Glycine	1.427	Zinc	3.31 × 10–3
Proline	1.045	Copper	0.671 × 10–3
Serine	1.167	Manganese	2.083 × 10–3
LIPIDS		Selenium	7.5 × 10–6
Fatty acids (total saturated)	6.893	**OTHERS**	
Fatty acids (total monounsaturated)	24.640	Carbohydrates (total)	21.51
Fatty acids (total polyunsaturated)	15.694	Dietary fiber	8.0
		Sugars (total)	4.18

(USDA 2011),

Drying can have effect on the nutritive content of groundnut and therefore should be done with care.(Adekanye *et al* 2009). Table 2.2 below shows a proximate analysis of nutrients in raw and dried groundnut.

TABLE 2.2: PROXIMATE ANALYSIS OF ARACHIS HYPOGEA (GROUNDNUT) SEEDS ON % DRY WEIGHT BASIS

groundnut) seeds on % dry weight basis Compositions	Raw	Sun-dried	Roasted

Moisture content	7.48	3.40	1.07
Ash content	1.48	1.38	1.41
Crude fibre	2.83	2.43	2.41
Crude fat/oil	46.10	43.80	40.60
Protein	24.70	21.80	18.40
Carbohydrate	17.41	27.19	36.11

(Adekanye *et al* 2009)

2.3 UTILISATION OF GROUND NUT CROPS

The uses of groundnut are diverse; all parts of the plant can be used. Peanuts are consumed in many forms such as boiled peanuts, peanut oil, peanut butter, roasted peanuts, and added peanut meal in snack food, energy bars and candies. Peanuts are considered as a vital source of nutrients. Peanuts are rich in calories and contain many nutrients, minerals, antioxidants, and vitamins that are essential for optimum health. (Yao,2004).

Non-food products such as soaps, medicines, cosmetics, pharmaceuticals, emulsions for insectcontrol, lubricants and fuel for diesel engines can be madefrom groundnut. The oil cake, a highproteinlivestock feed, may be used for human consumption. The haulms are excellent highprotein hay for horses and ruminant livestock. Groundnut shells may be used for fuel (fireplace"logs"), as a soil conditioner, for sweeping compounds, as a filler in cattle feed, as a raw sourceof organic chemicals, as an extender of resin, as a cork substitute, and in the building trade asblocks or hardboard .

Considering the importance of groundnut seeds, there is need for adequate preservation of this produce to avoid spoilage and also extend the shelf life as desired.

2.4 GRAIN STORAGE

The storage of foodgrains is normally done tomaintain their quality for extended periods and also to maintain a uniform supply of food for consumption, for the domestic and export market and to provide a buffer stock for contingencies such as drought floods and war. Millers, traders and other private entrepreneurs adopt it to speculate on good price. Like any post production operation, losses in storage are considered significant. And these are attributed mainly to spoilage, attacks by insects, mites, rodents, moulds and dry matter loss due to respiration.

The storability of grains is affected by their temperature and moisture content of the environment. Either or both factors must be reduced to ensure a conducive environment for storage. Most food crops generally deteriorate quickly in storage due to fungal infection if not properly dried to their safe moisture content (Bankole andAdebanjo, 2003).

The effect of fungal attack on food crops includes decreased nutritive value, change in color, reduced seed germination and mycotoxin production. The moisture content is known to play vital roles in the maintenance of seed quality in stores and hence their viability.

To reduce quality loss in stored products, rapid drying to low moisture is often emphasized, because all scenarios leading to mould contamination and subsequent damage relate to non-maintenance of stored products at safe moisture content (Awuah and Ellis, 2002; Bankole and Adebanjo, 2003)

2.5 BASIC PRINCIPLE OF DRYING

Drying is a complex operation involving transfer of heat and mass along with several rate processes, such as physical or chemical transformations (Otto *et al.*, 1994).

It occurs by supplying heat to the wet materials and thus vaporizing the liquid content. Generally, heat may be supplied by convection (direct dryers), conduction (contact or indirect dryers), and radiation or volumetrically by placing the wet material in a microwave or radio frequency electromagnetic field. Most industrial dryers are of the convective type with hot air or direct combustion gases as the drying medium. Almost all drying applications involve removal of water. All modes except the dielectric (microwave and radio frequency) supply heat at the boundaries of the drying object so that the heat must diffuse into the solid primarily by conduction.

Reduction of moisture from harvested crops has been found to deactivate enzymes or microorganisms that often cause undesired bio-chemical reactions and lead to quality deterioration in stored agricultural products (Jayaraman and Gupta, 2006). This process which is termed drying is greatly influenced by variations in composition and structure of food materials which often results in unique drying characteristic for different food product (Zogzas*et al.*,1996). Study of drying allows understanding of the controlling mechanisms involved and the prediction of the influence of the systemparameters on dryer design and performance. Drying kinetics is important in the analysis of moisture transfer process in food materials undergoing drying. In studying the kinetics of drying, thermo-physical properties and transport properties are usually integrated in drying models. Moreover, movement of moisture within a food material during drying is a complex process with various mechanisms (kinetics).

2.6 DRYING CURVES OF AGRICULTURAL PRODUCTS

Drying behavior of solids can be described by measuring the function of moisture content loss versus time. Continuous weighing, humidity difference and intermittent weighing are the often used methods (Mujumdar, 2004).

When drying crops using heated air, two drying periods generally occur viz: constant-rate period and falling rate period. Constant rate drying occurs with evaporation of surface water, while in falling rate period moisture movement is controlled by internal resistances. Moisture content as a function of drying time is plotted in figure 2.4 while an example of drying rate as a function of moisture content is shown in figure 2.5 for most agricultural materials.

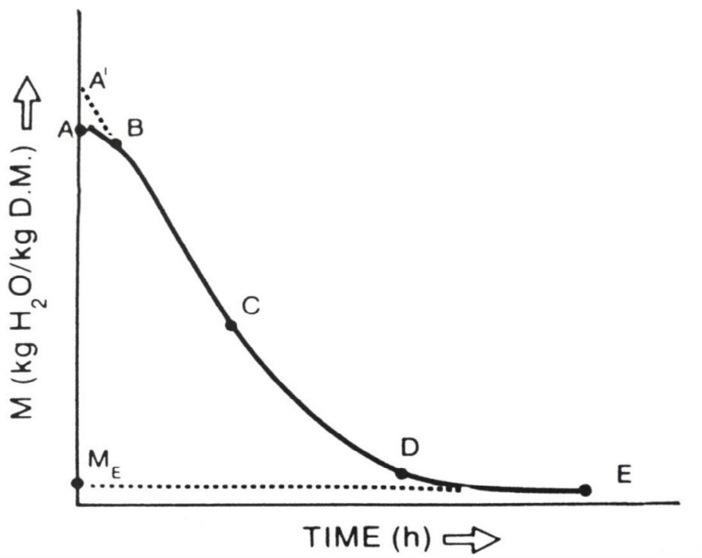


Figure 2.4: Drying Curve, Showing Moisture Content as a Function of Time (Source: Geankoplis 1993, Rizvi 1995)

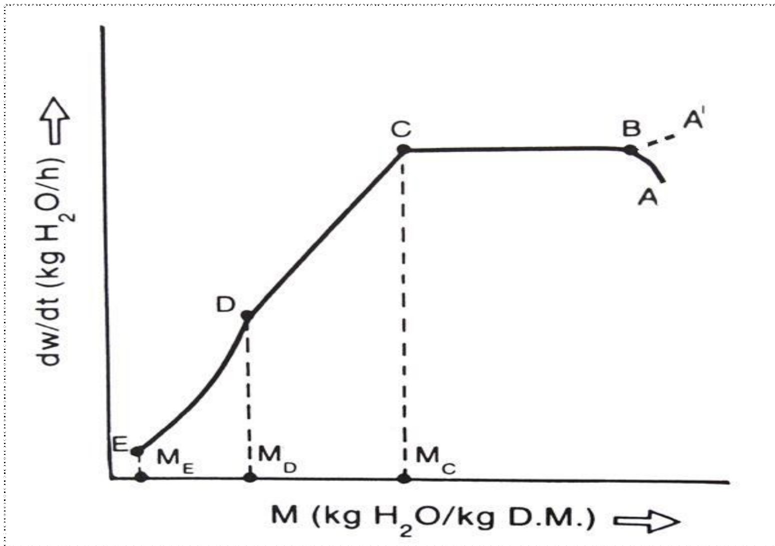


Figure 2.5: Drying Rate as a Function of Moisture Content

(Source: Geankoplis, 1993; Rizvi, 1995)

At zero time the initial moisture content is shown at point A. In the beginning, the solid is usually at a colder temperature than its ultimate temperature. Alternatively, if the solid is quite hot to start with, the rate may start at point A. Segment AB represents the initial unsteady-state, warming-up period. This initial unsteady-state period is usually quite short and it is often ignored in the analysis of times of drying (Geankoplis 1993).

BC is the constant rate period. The same points are marked in Figure 2.5, where the drying rate is plotted against the moisture contents (Rizvi 1995). During the constant rate period, the surface of the solid is initially very wet and a continuous film of water exists on the drying surface. This water is entirely unbound water and the water acts as if the solid were not present. The rate of evaporation under the given air conditions is independent of the solid and essentially the same as the rate from a free liquid surface (Geankoplis 1993).

The transition moisture content at which the departure from constant rate drying is first noticed is termed the critical moisture content, indicated by point C. At this point there is insufficient water on the surface to maintain a continuous film of water. In food systems, where liquid movement is likely to be controlled by capillary and gravity forces, a measurable constant rate period is found to exist. With some foods (structured), liquid movement is by diffusion, and therefore the water that is evaporated from the surface is not immediately replenished by movement of liquid from the interior of the food. Such foods are likely to dry without exhibiting any constant rate period. Hot air drying of apples, tapioca, sugar beet root and avocado are given as such foods without exhibiting any constant rate period (Rizvi 1995; Kaya *et al.*, 2007; Akpinar and Bicer 2003).

Between point C and D is termed the first falling rate period. During this period the rate of liquid movement to the surface is less than the rate of evaporation from the surface, and the surface becomes continually depleted in liquid water. The entire surface is no longer wetted, and the wetted area continually decrease in the first falling rate period until the surface is completely dry at point D. Beyond point D, the path for transport of both the heat and mass becomes longer and more tortuous as the moisture content continues to decrease. This period is called the second falling rate period. Finally, the vapor pressure of the solid becomes equal to the partial vapor pressure of the drying air and no longer further drying takes place.

The limiting moisture content at this stage to which a material can be dried under a given drying condition is referred to as the equilibrium moisture content (Me) (Rizvi 1995).

2.7 DRYING RATE CONSTANTS

Fick's diffusion equations are commonly used to determine the drying constant and effective moisture diffusivity during food and crop drying (Kaymak-ertekin, 2002). Hence the following Fick's second law of diffusion is applied to in conjunction with the experimental data, as given by equation (2.1).

$$\frac{\partial M}{\partial t} = \nabla^2 D_e M \qquad (2.1)$$

Where, M = moisture content (dry basis)

t = time (s)

D_e= effective diffusion coefficient (m^2/s), which describes how fast an object diffuses.

∇= Mass transfer gradient.

It is noticed that the drying curves took a linear form when the ln[MR] is plotted against time (Akpinar *et al*, 2003). The slope of the straight line obtained when logarithm of moisture ratio (*ln* MR) is plotted against time (t) represents the drying rate constant (k)

2. 8THIN LAYER DRYING MECHANISM

According to (ASAE, 2004b), there is a wide range of thin layer drying models, which have found application because of their ease of use. Thin layer drying equati vons are often empirical to describe drying phenomena in a unified manner regardless of the controlling mechanism. Many mathematical models have been used to describe the thin layer drying process of agricultural products. Most workers describe their thin layer drying experiments with suitable mathematical models which can be theoretical, semi-empirical or purely empirical (Madamba *et al.,*1996).

Thin layer drying equations are used to estimate the drying time of several products and also to generalize drying curves. A considerable amount of data has been reported in the literature regarding the thin layer drying model of various agricultural products, still continuous effort need to be carried out for further improvement of the drying process. The most important aspect of drying technology is the mathematical modelling of the drying processes and equipment where its purpose is to allow engineers to choose the most suitable operating condition for certain product. (Madamba *et al.,* 1996)

Referring to (ASAE, 1999), thin layer drying can be described as a drying of one layer sample particles or slices. Due to its thin layer characteristics, It is assumed that the temperature distribution is uniform, thus making thin layer drying suitable for lumped parameter models. The main mechanisms of drying are surface diffusion on the pore surfaces, liquid or vapour diffusion due to moisture concentration differences and capillary action in granular and porous foods due to surface forces (Erbay*et al.*, 2010). Generally, hygroscopic products dry in constant rate and subsequent falling rate periods and drying stops when equilibrium is established (Erbay*et al.*, 2010). During the constant rate period of drying, the physical form of the product and external conditions such as temperature, drying air velocity, direction of air flow and relative humidity have a great influence on the surface of the product being dried so called surface diffusion. When the surface film of the solids or particles appears to be dried and the moisture content has been reduced to its critical moisture content (Mc) then the first falling rate period begins. Unlike the constant rate periods, the falling rate period is controlled by liquid diffusion as a result of moisture concentration differences and the internal conditions of the product. The internal conditions such as moisture content, the temperature and the structure of the product play an important role in the falling rate periods. This phenomena will then be replaced by the second falling rate periods of drying namely vapour diffusion due to moisture concentration difference and also internal conditions of the products. It has been accepted that the drying phenomenon of biological products during falling rate period is controlled by the mechanism of liquid and/or vapour diffusion (Panchariya *et al.*, 2001). A complete drying profile consists of two drying stages; a constant rate period and falling rate period. However, not all grains follow this pattern (Duc*et al.*, 2011). In most cases, the falling rate period is reported as governed by diffusion mechanism in thin layer drying of agricultural products.

2.9 CROP DRYING MODELS

Drying involves the application of heat to vaporize the volatile substances (moisture) and some means of removing water vapor after its separation from the solid (Jayamaran and Gupta 2006). The drying process is based on heat and mass transfer whereby water migrates from the interior of the drying product onto the surface from which it evaporates, whereas heat is transferred from the surrounding air to the surface of the product. A part of this heat is transferred to the interior of the product, causing a rise in temperature and formation of water vapor, and the remaining amount is utilized in evaporation of the moisture from the surface (El-Ghetany 2006).

Mathematical modeling serves to be a most effective way to know the depth of drying in post-harvest processing of agricultural materials. Numerous mathematical equations can be found in literatures that describe drying phenomena of agricultural products.Generally, several mathematical models have been proposed for the evaluation of moisture transport behavior by either applying theoretical (Fick's first and second laws), semi-theoretical and empirical modeling (Midilli*et al.*,2002; Doymaz, 2005; Demir*et al.*,2007).

Theoretical model can be used to get an insight on the mechanism of moisture transfer during the three stages of drying (especially in the falling-rate period). However, from works reported by these early researchers it was observed that simplified assumptions such as constant diffusivity and one-dimension liquid diffusion sometimes resulted in inadequate prediction of the moisture distribution. A semi-theoretical model may not be able to explain the exact mechanism of moisture transport but it often gives good estimation by incorporating lump values of other effects into the model parameters.

Several types of drying methods and dryers, each better suited for a particular situation, have been used to monitor drying characteristics of a wide variety of food crops. There are many statistical-based models correlating experimentally obtained moisture data with time (t) in the literature. The most common among these used for food drying are tabulated in Table 2.4.

The most popular model for thin layer drying is the lumped parameter type like the Newton's equation (Kinsley*et al.,* 2007; Tunde-Akintunde and Afon 2009). Other authors that have worked extensively on drying models (theoretical, semi-theoretical and empirical drying models) include. Crank, (1956) independently published the general solution to the diffusion equation as a series of negative exponential terms, regardless of the geometry of the particles or the boundary conditions.

TABLE 2.4 THIN LAYER DRYING MODELS

S/No:	Model Name	Model
1	Lewis	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page	$MR = \exp[-(kt)^n]$
4	Henderson &Pabis	$MR = A.\exp(-kt)$
5	Logarithmic	$MR = A.\exp(-kt)+c$
6	Two Term	$MR =A.\exp(k_0t)+b\exp(-k_1t)$
7	Two Term exponential	$MR = A.\exp(-kt)+(1-)\exp(-At)$
8	Wang&Singh	$MR = 1+at+bt^2$
9	Approximation of diffusion	$MR = A.\exp(-kt)+(1-a)\exp(-kbt)$
10	Verma *et al.*	$MR = A.\exp(-kt)+(1-a)\exp(-gt)$
11	Modified Henderson&Pabis	$MR = A.\exp(-kt)+b\exp(-gt)+ c\exp(-ht)$
12	Simplified Fick"s Diffusion	$MR = A.\exp[-c(t/L2)]$
13	Modified Page II	$MR = \exp[-k(t/L2)^n]$
14	Midilli&Kucuk	$MR = A.\exp(-kt^n)+bt$

(Sources: Wang*et al.*, 2007; Diamante and Munro 1993; Akpınar and Bicer 2003; Toğrul and Pehlivan 2002; Midilli*et al.*,2002).

Moisture content was determined as adimensionless parameter denoted as Moisture Ratio (MR). The expression for $t_f$inTable 2.4 using the liquid diffusion model (Fick's second law of diffusion) is obtained by solving analytically the partial differential equation in equation 2.2 below:

$$\frac{\partial M_f}{\partial t} = D_{eff} \frac{\partial^2 M_f}{\partial x^2} \tag{2.2}$$

Subject to the following initial and boundary conditions:

$M_f = M_i$, everywhere in the slab at $t = 0$

$M_f = 0$, at $x = a$ (top, evaporating surface),

$\frac{\partial M_f}{\partial x} = 0,$ at $x = 0$ (bottom, non-evaporating surface)

More advanced models are, of course, available but their widespread use in the design of dryers is hampered by the need for extensive empirical information required to solve the governing equations.

Mujumdar (2000) provides a wide range of mathematical models of drying and dryers, and also discuss the application of various techniques for the numerical solution of the complex governing equations.

One simple approach to interpolating a given falling rate curve over a relatively narrow range of operating conditions was first proposed by Mujumdar, (2004) It is found that the plot of normalized drying rate $\nu = D_r/D_{r\text{-}c}$ versus normalized free moisture content $\eta = (M - M^*)/(Mc - M^*)$ was nearly independent of the drying conditions. This plot, called the characteristic drying rate curve, is illustrated in Fig.2.6.

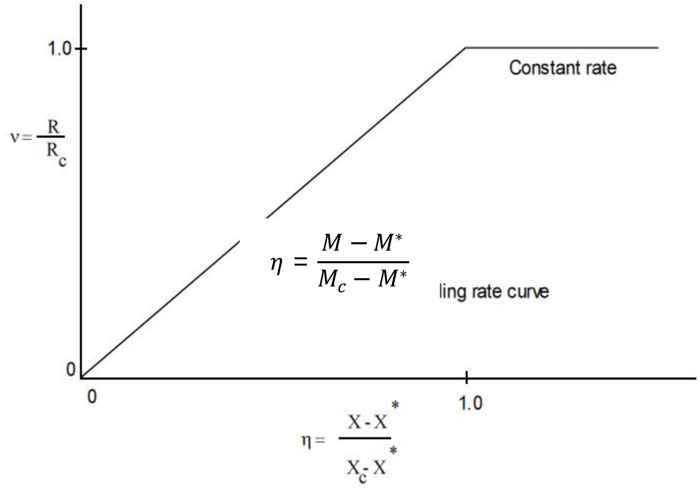


Fig2.6: Characteristic drying rate curve, (Mujumdar, 2004**)**

Thus, if the constant rate-drying rate, *Nc*, can be estimated and the equilibrium moisture content data are available, then the falling rate curve can be estimated using this highly simplified approach.

A mathematical description of the process is based on the physical mechanisms of internal heat and mass transfer that control the process resistances, as well as the structural and thermodynamic assumptions made to formulate the model. In the constant rate period, the overall drying rate is determined solely by the heat and mass transfer conditions external to the material being dried, such as the temperature, air velocity, total pressure and partial pressure of the vapor. In the falling rate period, the rates of internal heat and mass transfer determine the drying rate.

Modeling of drying becomes complicated by the fact that more than one mechanism may contribute to the total mass transfer rate and the contributions from different mechanisms may even change during the drying process. Diffusion mass transfer of the liquid phase, as discussed earlier, is the most commonly assumed mechanism of moisture transfer used in modeling drying that takes place at temperatures below the boiling point of the liquid under locally applied pressure. At higher temperatures, the pore pressure may rise substantially and cause a Hydro-dynamically driven flow of vapor, which, in turn, may cause a pressure driven flow of liquid in the porous material. For solids with continuous pores, a surface tension driven flow (capillary flow) may occur as a result of capillary forces caused by the interfacial tension between the water and the solid. In the simplest model, a modified form of the Poiseuille flow can be used in conjunction with the capillary force equation to estimate the rate of drying. Geankoplis (1993) has shown that such a model predicts the drying rate in the falling rate period to be proportional to the free moisture content in the solid. However, at low moisture contents, the diffusion model may be more appropriate. Solutions of the Fickian second law equation are summarized in table 2.5

TABLE 2.5: SOLUTIONS OF FICK'S SECOND LAW OF DIFFUSION FOR SOME SIMPLE GEOMETRY

Geometry of the material	Boundary conditions	Dimensionless average free moisture content
Flat plate of thickness 2b	t=0;-b<z<b; M=M_o $t > 0; z = \pm b; M = M^*$	$M = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)}\exp\left[-(2n-1)^2\frac{\pi^2}{4b}\left(\frac{D_L t}{b}\right)\right]$
Infinitely long cylinder of radius R	t=0;0<r<R; M=M_o $t > 0; r = R; M = M^*$	$M = 4\sum_{n=1}^{\infty}\frac{1}{R^2\alpha_n^2}exp(-D_L\alpha_n^2 t)$ Where α_n are positive roots of the equation $J_0(R\alpha_n) = 0$
Sphere of radius R	t =0;0<r<R; M=M_o t > 0; r=R; M=M^*	$M = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[\frac{-n^2\pi^2}{R}\left(\frac{D_L t}{R}\right)\right]$

(Source: Pakowski and Mujumdar, 1995)

The moisture flux due to capillarity can be expressed in terms of the product of a liquid conductivity parameter and moisture gradient. In this case, the governing equation has, in fact, the same form as the diffusion equation. For certain materials and under conditions such as those encountered in freeze drying, a “receding-front” model involving a moving boundary between “dry” and “wet” zones often describes the mechanism of drying much more realistically than does the simple liquid diffusion or capillarity model. Examination of the freeze drying of a thin slab indicates that the rate of drying is dependent on the rate of heat transfer to the “dry-wet” interface and the mass transfer resistance offered by the porous dry layer to permeation of the vapor which sublimes from the interface. Because of the low pressures encountered in freeze drying, Knudsen diffusion may be significant.

2.9.1 MODELING OF FIXED-BED DRYING

Modeling of drying process involves the following:

- Vapour/air equilibrium (Psychrometrics)
- Moisture equilibrium (isotherms)
- Drying kinetics
- Residence time and drier conditions
- Cost analysis

American Society of Agricultural Engineers (ASAE) has described thin layer in relation to thickness of a grain bed within which all the kernels have almost the same exposure to the drying medium. ASAE (2003b, 2004b, 2005b)refer to thin layer as a uniform bed of grain that has a depth (thickness) of not more than three layers of particles which is fully exposed to an air stream during drying.

Thin layer models describe the drying phenomena in a unified way regardless of the controlling mechanism. They have been used to estimate drying times and generate drying curves of several products such as tea (Temple and Boxtel, 1999), Rapseed (Correa *et al.*, 1999), apricots (Togrul and Pehlivan, 2002). In each case, the models were developed by correlating the moisture content of the product to the drying parameters. By considering the deep bed as series of thin layers, the validity of deep-bed model was found to depend on the goodness of fit of the thin-layer drying models. Hence, the thin-layer drying models help to define the mass and energy transfer mechanisms that give rise to simulation and optimization of the design of drying systems (Thongprasert, 2000; Chen and Wu, 2001; Iguaz *et al.*, 2003)

Models of this kind can easily be found in the literature, mostly for regular shaped geometries.

Wongwises and Thongprasert (2000) claimed that the difference in heat and mass transfer processes in paddy grain and other cereal grains is due to the presence of husks present in paddy.

Shei and Chen (1999) used a single-term diffusion model in their drying study and reported that the model did not appear to be adequate for rice dying at the beginning of the drying period.

Queroz *et al* (2000) developed a model for simulation of moisture diffusion during the drying process of the grain using Finite element method concluded that it predicted the temperature of the air and grain as well as the moisture movement inside the grain kernel. Based on differential equations and applications of the principles of momentum, mass and energy balances, Izadifar and Mowla (2003) developed a model which they used to simulate the drying of grains in a cross-flow continuous fluidized bed dryer.

It is generally assumed that water transfer in solid matter takes place through molecular diffusion. Most current method for studying mass transfer in an unstable condition, during drying of foodstuff, is the Fick's equations (Vega *et al.*, 2007). Most theoretical models studied in thin layer drying of various foodstuffs are a result of solving the Fick's second law. Though much has not been reported on drying studies of melon seeds, the flat shape of the seeds makes it easy to adapt the solution of Fick's law of diffusion for a slab by estimating the model constants of one term and two terms of the series solution.

2.10 DRYING KINETICS

According to Jayarama and Gupta 2006, drying rate of fully exposed grain kernels is divided into an initial warming up period, constant rate and falling rate periods. These rate periods are illustrated in figure 2.6

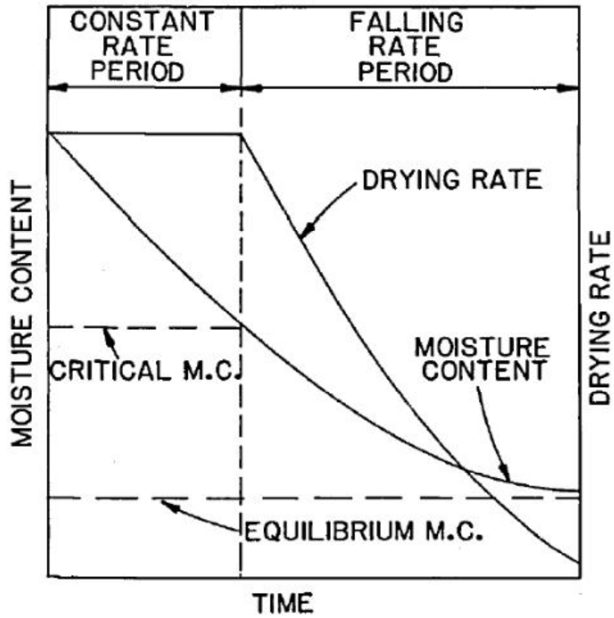


Fig 2.7: Constant and falling rate periods in thin-layer drying of high moisture grain (Jayaraman and Gupta 2006)

Experimental evidence shows that a single drying constant almost invariably over-estimates the drying rate in the final stages of drying. (Jayaraman and Gupta 2006)During the convective drying, heat-transfer between the sample and the surroundings is controlled by the humidity-ratio of the air at the surface, the temperature of the plenum and temperature of the sample surface (Bablis *et al.*, 2004). Heated-air drying refers to the removal of free and bound moisture from a sample, by using heat energy in a specially designed dryer. During drying, there is simultaneous transfer of heat, to evaporate and transfer moisture to the surface and as vapor from the surface into the hot air stream, within an optimal period of time.(Jayaraman and Gupta 2006)

Movement of moisture through the sample is in the form of water-vapor within the cell-cavities and bound water. Bound water is hydrogen-bonded to the hydroxyl groups of the polysaccharides. Therefore, the driving force responsible for moisture-transport is a combination of diffusion along the moisture concentration-gradient and difference of vapor-pressure due to temperature gradient. The transfer of liquid within a drying sample may occur by the following mechanisms:

I. Diffusion in the continuous homogeneous solids,
II. Capillary flow in the granular and porous solids,
III. Flow caused by shrinkage and pressure gradients, and
IV. Flow caused by sequence of vaporization and condensation.

(Jayaraman and Gupta 2006)

The attainment of critical moisture-content depends on the drying conditions (humidity and temperature) and the characteristics of the samples (shape, size, density, area and specific heat-capacity). Moisture in excess of free moisture-content, in equilibrium with the air, can only be removed upon prolonged contact of the sample with hot drying air.

The general theory of drying is based on the consideration of inert solid wetted with moisture and exposed to heated current of air. The air supplies the sensible heat, heat of vaporization and also acts as a carrier of the evaporated moisture. Thus drying is a process of simultaneous heat and mass transfer. For the purpose of analysis, drying is usually subdivided into two categories, namely;

i. Single kernel or thin layer drying: this is considered as the drying process involving material depth of not more than ten particles (depth$< \boldsymbol{10particles}$) diameter.

ii. Deep bed drying: this consists of agglomeration of particles above ten particle diameter ($\boldsymbol{depth > 10particlediameter}$).

Since warming up period is often short and represents only 0.25% of the total drying period/time, it is often neglected in drying analysis.

At constant rate period, the rate of mass transfer balances the rate of heat transfer and so the temperature of the drying surface remains constant at the wet bulb temperature of the drying air. The driving force causing vapor movement through the stagnant air film is the vapor pressure gradient between the drying surface and the main air stream. The rate of mass transfer can be put as shown in Equation 2.3:

$$\left.\frac{dm}{dt}\right|_{const.} = -k_g A(p_s - p_a) \qquad (2.3)$$

$$where, -\left.\frac{dm}{dt}\right|_{const.} = dryingrate$$

$k_g = masstransfercoefficient, kg/m^2$

A=surface area of drying material, m^2

P_s =water vapor pressure at material surface

P_a= partial pressure of water vapor in air

The rate of heat transfer to the drying surface is given in Equation 2.4

$$\left.\frac{dQ}{dt}\right|_{const.} = h_c A(T_a - T_s) \qquad (2.4)$$

h_c= convective heat transfer coefficient, J/hm^{2o}C

T_a=dry bulb temperature of air

T_s = temperature of the drying surface, ^oC

Since a state of equilibrium exists the following equation can be written;

$$\left.\frac{dm}{dt}\right|_{const.} . L = \left.\frac{dQ}{dt}\right|_{const.} \quad (2.5)$$

Where, L = heat of vaporization of moisture at T_s, J/Kg

Combining equations 2.4 and 2.5, gives equation 2.6

$$\left.\frac{dm}{dt}\right|_{const.} = -\frac{h_c.\acute{A}}{L.d.\rho_b}(T_a - T_s) \quad (2.6)$$

Where, $\rho_{b=bulkdensityofthematerial.}$

Rearranging and integrating equation 2.6,

$$\int_{m_o}^{m_c} dm = \frac{h_c.\acute{A}}{L.d.\rho_b}(T_a - T_s)\int_{t=0}^{t=t_c} dt \quad (2.7)$$

$$m_0 - m_c = \frac{h_c A(T_a - T_s)}{L.d.\rho_b}.t_c \quad (2.8)$$

In this equation, $m_0 - m_c$, canbe defined as the amount of moisture removed during constant rate period. m_o and m_c are initial and critical moisture content respectively.

The rate of drying during the constant rate period is a function of three parameters namely, air velocity, air temperature, and air humidity. From equation (2.7), time for attaining critical moisture content (m_c), which terminates the constant rate period can be predicted as Equation 2.9

$$\boldsymbol{t_c} = \frac{L.d.\rho_b}{h_c}\left[\frac{m_o - m_c}{T_a - T_s}\right] \quad (2.9)$$

Where, $\boldsymbol{t_c = duration\ of\ the\ constant\ rate\ period}$ and

d = depth of grain bed

To predict the drying rate, it is not only the extent of macroscopic convective heat-and-mass-transfer, associated with the sample and the surroundings in the drying chamber that have to be considered, but also the mechanisms of microscopic heat and mass diffusion within the sample must be included in the analysis. The rate of heat or mass-transfer is determined by multiplying the respective transfer-coefficient and the driving force.

The drying bed is modeled by considering a thin layer of a slab-shaped crop bed of thickness dz and then combining many of such thin layers to form the deep bed of thickness z_o. By consecutively calculating the air and moisture changes that occur during short intervals of time as the drying air passes from one layer to the next, the continuous drying process was simulated. The procedure adapted assumes that each layer is dried for a short time interval, dt, using air leaving the preceding layer. The process is repeated with consecutive short increments of time until the desired final moisture content of the crop bed is achieved. Relevant independent partial differential equations are normally needed to predict the changes in the crop temperature, moisture content, air temperature and relative humidity. Changes in the gas phase concentration are assumed negligible compared with that of the solid phase changes (Pakowski and Mujumdar, 1995). These equations are: the drying rate equation, the mass balance equation on the drying air, the heat balance equation on the drying air and the heat balance equation on the crop (Cenkowski *et al.*, 1993).

2.11 MOISTURE DIFFUSION COEFFICIENT (D_{eff})

The water in the grain mass needs to be transferred to the grain surface in order to be removed by air. This diffusion process in porous moist solids depends on the nature of the material, moisture content and moisture bonding (Aguerre& Suarez, 2004). Partial pressure difference which determines diffusion and moisture migration is driven by partial pressure gradient. When the air relative humidity that surrounds a kernel is lower than the relative humidity for moisture equilibrium at a given temperature, the water on the grain surface is evaporated into the air. This reduction in the surface water creates a partial pressure difference within the kernel which drives the diffusion process associated with water.

Once the drying rate constant (k) was determined from the slope of the regression line the effective diffusion co-efficient (D_{eff}) can be calculated as follows:.

Singhanat and Saentaweesuk, (2011), reported that effective moisture diffusivities vary in the range of 5.009×10^{-11} to 1.735×10^{-10} m^2s^{-1} for most food materials in the temperature range of 40–60 °C. The moisture diffusivity has been reported to be influenced by air temperature and air velocity. Akpinar,*et al* (2003) and Thorat, *et al* (2010) reported that the values increased with increasing air temperature and velocity. Okos,*et al.*(1992) have given an extensive compilation of $D_{eff}$and $E_a$values for various food materials.

Zogzas ,*et al.*(1996) provide methods of moisture diffusivity measurement and an extensive bibliography on the topic.

In addition to being dependent on geometric shapes, diffusivity depends as well on the drying conditions. At very high activity levels, no differences might be observed but at lower activity levels, the diffusivities may differ by an order-of-magnitude due to the inherently different physical structure of the dried product. Thus, the effective diffusivity is regarded as a lumped property that does not really distinguish between the transport of water by liquid or vapor diffusion, capillary or hydrodynamic flow due to pressure gradients set up in the material during drying. Further, the diffusivity values will show marked variations if the material undergoes glass transition during the drying process.

2.12 ACTIVATION ENERGY OF MOISTURE DIFFUSION

Applying parameters in the solution of Fick's equation of diffusion equation as shown in equation (2.10 and 2.11), it may be noted that the drying rate constant, k is a function of the square of thickness (L) and diffusion coefficient (D), viz:

$$\boldsymbol{k = \frac{\pi^2 D_e}{L^2}} \quad (2.10)$$

Equation 2.10 can be written as;

$$\boldsymbol{k = \pi^2 D_e (L)^{-2} = A(L)^{-n}} \quad (2.11)$$

Where, $\boldsymbol{A = \pi^2 D_e}$ and, n=2. (Islam, 2012)

Earlier researchers reasoned that since external resistance due to thickness to mass transfer is negligible and that simultaneous heat and mass transfer effects are taken into account, the theoretical value of the exponent of the power law equation (2.11) should be 2, but Islam, (1992), reported that the above conditions are not always satisfied.

An Arrhenius-type equation presented a strong temperature effect on the diffusion coefficient. The plots of the logarithm of moisture Diffusivity (D_{eff}) versus the inverse of the drying temperature (1/T) gave a straight line. The relationship was as as shown in eqn 2.12(Islam, 2012):

$$\boldsymbol{D_{eff} = D_0 e^{-E_a/RT_{abs}}} \qquad (2.12)$$

Where, D_{eff} =effective moisture diffusion coefficient (m^2/sec)

D_o = the constant of integration and is usually referred to as a frequency factor when discussing Arrhenius equation, m^2/sec,

E_a = activation energy of diffusion of water, KJ/mole

R = gas constant, KJ/mole, ^{o}k

T_{abs} = absolute temperature, ^{o}k

Equation 2.1 can be put in linear form by taking the logarithm of both sides to get the following:

$$\boldsymbol{lnD_{eff} = lnD_o - \frac{E_a}{RT_{abs}}} \qquad (2.13)$$

From equations 2.12& 2.13, it can be seen that when diffusion coefficient (D_{eff}) is plotted against the inverse of the product of absolute temperature and universal gas constant on semi-logarithmic co-ordinates, it produces a straight line. The slope of the straight line represents the activation energy. Thorat,*et al* (2010) reported Activation energy of 35.675 $kJ.mol^{-1}$ for drying of ginger slices. Bablis,*et al* (2004) reported the value of the activation energy to vary from 30.8 to 48.47 kJ/mol for figs while Aghbashlo,*et al* (2008) reported that activation energy (E_a) value varied within 110.837–130.61 kJ/mol for different air velocities with beriberi fruit. Garau, *et al*(2006) reported value of 36.4 kJ/mol for orange skin. If the activation energy in a reaction is low, a greater proportion of the collisions between reactants will result in reactions. If the temperature of the system is increased, the average heat energy is increased, a greater proportion of collisions between reactants result in reaction, and the reaction proceeds more rapidly. The activation energy and rate of a reaction are related by the equation $k = A\exp(- E_a / RT)$, where k is the rate constant, A is a temperature-independent constant (often called the frequency factor), *exp* is the function e^x,Ea is the activation energy, R is the universal gas constant, and T is the temperature. This relationship was derived by Arrhenius in 1899. Because the relationship of reaction rate to activation energy and temperature is exponential, a small change in temperature or activation energy causes a large change in the rate of the reaction. Activation energies are usually determined experimentally by measuring the reaction rate k at different temperatures T, plotting the logarithm of k against $1/T$ on a graph, and determining the slope of the straight line that best fits the points. In drying process the effective moisture diffusivity (D_{eff}) is analogous to the rate constant (k).

CHAPTER THREE

MATERIALS AND METHODS

3.1 THEORETICAL CONSIDERATION/CONCEPT

The two important variables in drying studies are the air-mass flow rate and the temperature at the inlet to the dryer. Hot air is blown into the dryer and air temperature is monitored by regulating the heat source output with the assistance of sensors installed inside the drying chamber to monitor the air and product temperatures. In modeling a convective hot-air drying process, the following assumptions have been made:

1. Temperature distribution inside the drying products is uniform,
2. Air is assumed an ideal gas.
3. The system is properly insulated and there is no air or heat leakage (Adiabatic).

Based on the above assumptions and conservation laws for mass and energy, model equations were formulated and solved to obtain the required parameters needed to describe the drying process of groundnuts in the drying chamber.

3.2 EXPERIMENTAL VALIDATION PROCEDURE

Under the varying factors of temperature, relative humidity, air flow rate and moisture content the drying characteristics of the groundnut samples were determined experimentally and fitted into the developed drying models.

Emphasis was placed on determining the parameters that characterize the drying of the groundnut under the prevailing conditions of temperature, relative humidity, air velocity and material's moisture content. These experimental factors were measured throughout the duration of each drying experiment. The model parameters were determined by statistical methods using experimental data. Matlab software was used in data analysis involving computations, graphs and simulation. The validity of the drying models was compared with experimental data, while the model efficiency was estimated by the Root Mean Square Error (RMSE), Sum of Square Error (SSE), and coefficient of determination (R^2).

3.3 DETERMINATION OF PHYSICAL CHARACTERISTIC OF GROUNDNUT SEEDS

The samples were at the moisture level of 67% (db) when physical characteristics were determined.

(A) SIZE, SURFACE AREA AND SPHERICITY:-In order to determine the average size of the seeds, 100 seeds were randomly drawn from the bulk sample. For each individual seed, three mutually perpendicular axes namely major diameter (L_1), intermediate diameter (L_2) and minor diameter (L_3) were measured using an electronic caliper (model QLR digit-IP54, China) with an accuracy of 0.001 mm. The arithmetic mean diameter (D_a, mm), equivalent diameter (D_e, mm), and the geometric mean diameter (D_g, mm) of the seeds were calculated using the following relationships, respectively (Mohsenin, 1978):

$$\boldsymbol{D_a} = \frac{\boldsymbol{L_1+L_2+L_3}}{\boldsymbol{3}} \tag{3.1}$$

$$\boldsymbol{D_e} = \frac{D_a+\boldsymbol{D_g}+\boldsymbol{D_s}}{\boldsymbol{3}} \tag{3.2}$$

$$D_g = (L_1 . L_2 . L_3)^{1/3} \quad (3.3)$$

The degree of sphericity, $\emptyset_M$(%), of the samples were calculated using equation 3.4

$$\emptyset_M = \frac{(L_1 + L_2 + L_3)^{1/3}}{L} \quad (3.4)$$

(Mohsenin, 1978).

The surface area S_M(mm^2) was determined using equation 3.5 below

$$S_M = \pi D_g^2 \quad (3.5)$$

(McCabe *et al.*, 1986).

The shape factor (Z) was calculated using equation 3.6

$$Z = \left(\frac{\pi}{6}\right)\left(\frac{d_e}{d_g}\right)^3 (\emptyset_M) \quad (3.6)$$

(Razavi and Akbari, 2005)

(B) VOLUME AND BULK DENSITY:- Bulk density is simply the ratio of the mass of the seed sample to its bulk volume, where as True density is the ratio of mass of the sample to the true volume of the particles *i.e.* excluding the volume of any internal pores. To obtain the mass, each groundnut was individually weighed on a precision electronic balance (Ohaus, Pine Brook, NJ USA) of ±0.001 g accuracy. The seed volume was determined using the liquid displacement method (Mohsenin, 1986). Toluene (C_7H_8) was used as the displacement liquid because it is absorbed by seeds to a lesser extent than water and its surface tension is low, so that it fills even shallow dips in a seed and its dissolution power is low (Ogut, 1998). Ten replicates of the samples were made and used for the conduct of this experiment with groundnut seeds. The volume (V, in m^3) was calculated using equation 3.7 (Mohsenin, 1986).

$$\boldsymbol{V} = \frac{\boldsymbol{M_{td}}}{\boldsymbol{\rho_{tol}}} = \frac{(\boldsymbol{M_{ps}} - \boldsymbol{M_p}) - (\boldsymbol{M_{pts}} - \boldsymbol{M_t})}{\boldsymbol{\rho_{tol}}} \tag{3.7}$$

where: $M_{td}$is unit mass of seed, $M_t$is mass of pycnometer filled with toluene; M_p, mass of pycnometer; M_{pts}, mass of pycnometer filled with toluene and sample; M_{ps}, mass of pycnometer and sample; and $\boldsymbol{\rho_{tol}}$is density of toluene.

The true density (($\boldsymbol{\rho_t}$) , kg m^{-3}) of groundnut seed was obtained equation 3.8

$$\boldsymbol{\rho_t} = \frac{\boldsymbol{M_{ps}} - \boldsymbol{M_p}}{\boldsymbol{V}} \tag{3.8}$$

(Razavi and Milani, 2006).

Bulk density($\boldsymbol{\rho_b}$), is based on the volume occupied by the bulk sample as poured into a container of known volume. In order to measure the bulk density, the groundnut seeds were poured into a calibrated container of known volume and weight, up to the top from a height of about 15 cm, the increase in volume was recorded. The seeds were not compacted in any way. The ratio of the mass and volume was expressed as bulk density.

The porosity was calculated from the data of bulk density($\boldsymbol{\rho_b}$)) and true density measurements using equation 3.9 (Mohsenin, 1986).

$$\boldsymbol{\varepsilon} = \left(\mathbf{1} - \frac{\boldsymbol{\rho_b}}{\boldsymbol{\rho_t}}\right)\mathbf{100} \tag{3.9}$$

3.4 SAMPLE PROCUREMENT AND PREPARATION

The experiment to accomplish the desired objectives was performed in the laboratories of the Department of Mechanical Engineering, School of Engineering and Engineering Technology, NnamdiAzikiwe University, AwkaAnambra state Nigeria. Groundnuts (*Kerstingiella geocarpa Harms specie*) were procured from a farm in Anam, Anambra-west Local Government area of Anambra state at 67% moisture content (db). The groundnuts were removed from the pods and left to dry in open air; it was turned every hour to ensure uniformity during drying.

3.5 INSTRUMENTATION

The following apparatus were used in the model validation experiments.

i. The developed dryer.

ii. Built-in air anemometer to measure air flow rate.

iii. Installed digital thermometers to measure temperature.

iv. Software: Matlab, Ms-Excel, ESB Unit Converter and Vaisala Humidity calculator (Psychrometer).

The dryer (Fig 3.2) consists of a fan, air heaters, drying chamber and instruments for measurement of air flow rate (hot air anemometer). The airflow rate was adjusted by the fan speed control. The heating system consists of electric hot plate placed at the plenum chamber of the drying apparatus. The drying tray was placed in the heated air stream. Digital thermometers (Multi-thermometers, model H-9296 China), with reading accuracy of 0.01ºC was used in temperature measurement.

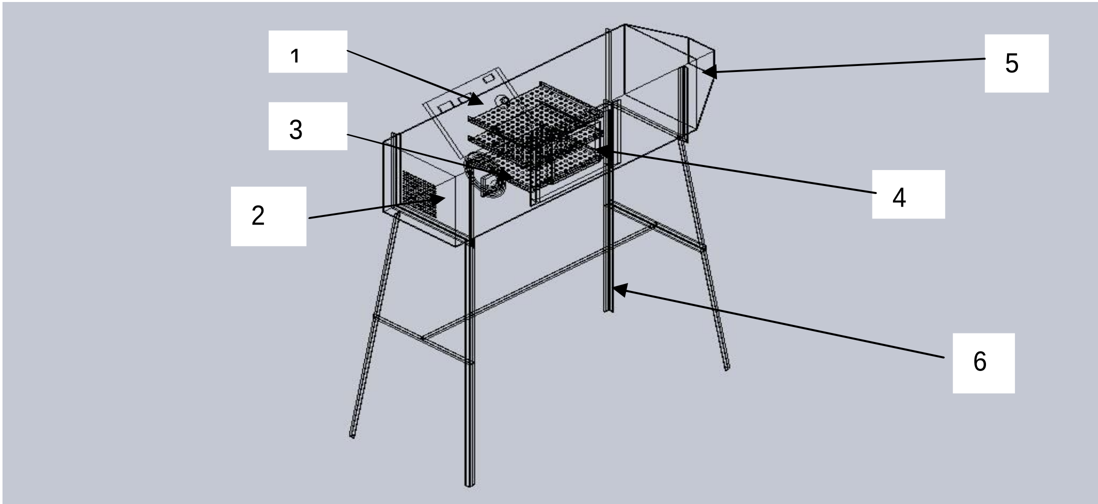


Fig 3.1 Cut-away View of the dryer (internal view); 1=Control panel, 2=Fan housing, 3=Electric heater, 4=Drying (crop) trays, 5=Exhaust openning, 6= Frame support (Legs).

Fig 3.2A pictorial view of an electrical heated dryer used for the experiment

The wet-bulb and dry-bulb temperatures were determined and used to calculate the relative humidity levels of the drying air. The wet bulb temperature was obtained by immersing the sensing bulb of the thermometer in a wet wick and placed in the stream of air. The temperature indicated by such thermometer is recorded as the wet bulb temperature. The velocity of air passing through the system was measured using hot air anemometer.

3.6 EXPERIMENTAL DESIGN

The experiments were designed in Split Plot Design, under three air velocities of 0.6, 1.0, 1.5 m/s and three temperatures of 45, 55 and 65^{o}C. This range of temperature was considered suitable for most agricultural materials, especially when drying for seeds. Some authors have argued that air velocity does not have significant influence on the drying kinetics of crops. Therefore the low range of air velocity was considered for the reasons of cost in the energy requirement. The layout of the treatment combinations is shown in table 3.1:

TABLE 3.1: THE EXPERIMENTAL DESIGN LAYOUT

Air Velocity, (m/s)	Temperature, (^{o}C)		
	T_1	T_2	T_3

V_1			
V_2			
V_3			

3.7 EXPERIMENTAL PROCEDURE

The experiments involved the following procedure:

i. Sample preparation
ii. Determination of physical characteristics of the product
iii. Determination of moisture content of the product
iv. Drying the seeds with the set conditions and noting the weight

Drying commenced from 8 a.m. till 6 p.m. daily and terminates when there are little or no differences in the groundnut's moisture content. In order to simulate the actual practices of artificial drying, the groundnuts were dried using an oven at air temperature of 45-65°C, the groundnuts were left tempered at room temperature overnight. The purpose of this step is for the moisture within the groundnuts to redistribute from the internal to the outer layer of the groundnut (testa) because the testa will generally dry faster than the cotyledon layer in hot air drying. Moisture content of the groundnut seeds was taken every 15 mins by measuring the weight of the seeds using a digital top balance instrument (Ohaus, Pine Brook, NJ USA) of ±0.001 g accuracy.

The variable parameters considered in the experiments were drying air velocity and temperature. The experiments were conducted at three air flow rates (0.6, 1.0 and, 1.5 m/s), the air temperature depended on the voltage control gadget setting.

Three replicates each, of the experiments, were conducted to reduce experimental error. 400g of the sample was used for each run of the experiments. The fan and heater were started and the drying temperature and air flow were allowed to run without load until stabilized condition was observed, when all the indicators are steady at a set value. Thereafter, the drying chamber was loaded with the samples for the experiments. The sample was weighed every fifteen minutes until steady weights were observed in two or more consecutive weighing. The initial weight of the tray (355.6g) was subtracted from the weight of sample plus drying trays at each interval to note the weight loss of the sample. From this weight loss, the moisture content at each point was determined using the following expression:

$$\boldsymbol{M_{t(db)} = M_o\%_{(db)} - \left(\frac{100(W_o - W_t)}{(1 - M_{o(wb)})W_o}\right)} \tag{3.10}$$

Where, $M_{t(db)}$ =Moisture content at any time %(db)

M_o% (db) = initial moisture content % (db)

M(db) = initial moisture content % (wb)

W_t= weight of sample at any time, g

W_o=initial weight of sample, g

Drying was continued until the moisture content of the sample reached equilibrium with the drying air. This state was observed when two or three consecutive weighing showed no significant variation or change in value. The average moisture content of the samples for each weighing period was calculated based on the initial mass and final moisture content of the samples. After each drying experiment, the sample moisture content was determined and termed the final moisture content. The total amount of moisture removed was calculated using equation 3.11.

$$\boldsymbol{MC\ (w.b)} = \frac{\boldsymbol{m_i - m_f}}{\boldsymbol{m_i}} \tag{3.11}$$

The drying air temperatures, drying air velocity and sample weight were continuously measured and recorded every 15 min during the drying experiments. The speed of the air was measured by a speed meter (hot wire anemometer, model 20004 AHYK), with the precision of 0.01m/s, while the temperature was measured by series of digital thermometers inserted at various points in the dryer. The sensing bulb of the digital thermometers were covered by wick and constantly kept wet for measurement of wet bulb temperature. The experiments were carried out under varying conditions of the drying air. There were three temperature levels (45^{o}C, 55^{o}C and65^{o}C) and three air flow rates (0.6, 1.0, and 1.5). The data were analyzed and used for determination of the drying parameters of groundnutseeds.

3.8 DETERMINATION OF MOISTURE CONTENT

Moisture contents of the product sample were determined using the standard oven method (AOAC 1999). Metal trays of known weight were loaded with known weight of the samples and put in an oven set at constant temperature of 103^{o}C. The dishes and samples in oven were subjected to continuous weighing until three subsequent constant weights were recorded. For the purpose of this study, triplicate 300g samples were put in an oven at 103ºC until constant weight was reached (minimum 24 h). The metal dishes were taken out from the oven and weighed at every fifteen (15) minutes in the first one hour, at every thirty (30) minutes in the second hour, then at after every two (2) hours until constant weights are reached in the within twenty four (24) hours . Prior to weighing, the metal dishes were allowed to cool down to the room temperature in desiccators for five (5) minutes to eliminate buoyancy effect. It was supposed that the drying samples in the dishes possessed stable weight when the change in their weight was significantly constant. Moisture contents were recorded as per cent dry-basis (% w.b.). The amount of moisture was calculated using equation 3.11.

3.9 DETERMINATION OF RELATIVE HUMIDITY.

Because of the inconvenience in the use of hygrometer in the measurement of the relative humidity of the drying air, it was calculated using the experimental values of dry bulb and wet bulb temperatures respectively, (in ^{o}C) with the help of VAISALA Humidity calculator. The VAISALA Humidity calculator window is shownin figure 3.3

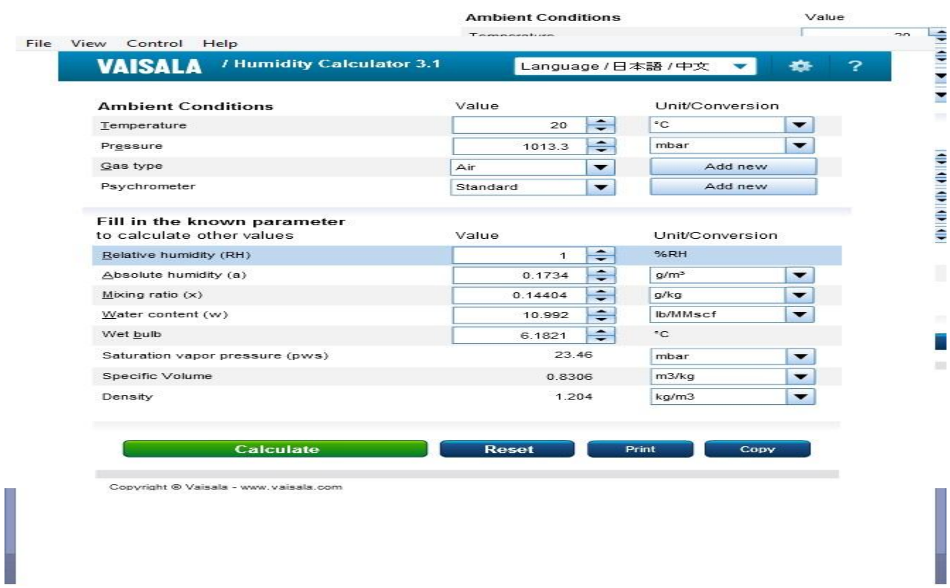


Fig 3.3:Viasala Software Window for determining air properties

Table 3.2: Selected thin-layer drying models

Model Name	**Model Equation**	**Equation Number**	**References**
Newton	$\mathbf{MR = exp\ (-kt)}$	3.12	(Soysal *et al.*, 2006)
Page	$\mathbf{MR = exp^{-kt^n}}$	3.13	(Sarimeseli, 2011)
Logarithmic	$\mathbf{MR = aexp^{(-kt)} + c}$	3.14	(Akpinar *etal.*, 2006)
Henderson and Pabis	$\mathbf{MR = aexp^{(-kt)}}$	3.15	(Zarein *et al.*, 2013)
Two-Term	$\boldsymbol{MR = aexp(-k_1 t) + bexp(-k_2 t)}$	3.16	(Zarein *et al.*, 2013)

3.10 DETERMINATION OF EFFECTIVE MOISTURE DIFFUSSIVITY AND ENERGY OF ACTIVATION IN DRYING.

In drying process the effective moisture diffusivity (D_{eff}) is analogous to the rate constant(k). Activation energies are usually determined experimentally by measuring the reaction rate k at different temperatures T, plotting the logarithm of k against $1/T$ on a graph, and determining the slope of the straight line that best fits the points.

If the activation energy in a reaction is low, a greater proportion of the collisions between reactants will result in reactions. If the temperature of the system is increased, the average heat energy is increased, a greater proportion of collisions between reactants result in reaction, and the reaction proceeds more rapidly. A catalyst increases the reaction rate by providing a reaction mechanism with lower activation energy, so that a greater proportion of collisions result in reaction. The activation energy and rate of a reaction are related by equation 3.17 below

$$k = A\exp(- E_a / RT) \qquad (3.17)$$

where:

k is the rate constant,

A is a temperature-independent constant (often called the frequency factor),

exp is the function e^x,

Ea is the activation energy,

R is the universal gas constant, and

T is the temperature.

This relationship was derived by Arrhenius in 1899. Because the relationship of reaction rate to activation energy and temperature is exponential, a small change in temperature or activation energy causes a large change in the rate of the reaction.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

4.1.1 PHYSICAL CHARACTERISTICS OF GROUNDNUT SEEDS

Selected physical characteristics of groundnut were calculated from the measured three perpendicular principal dimensions of major diameter (L_1), intermediate diameter (L_2) and minor diameter (L_3). Summary of these data are presented in table 4.1.

Table 4.1: Measured Physical characteristics of groundnut seeds

S/N	MEASURED PHYSICAL CHARACTERISTICS	VALUE
1	Moisture Content (M), (%) (db)	67±0.18
2	Major diameter (L_1), mm	17.299 ± 0.806
3	Intermediate diameter (L_2) mm	9.422± 0.621
4	Minor diameter (L_3) mm	7.396± 0.815
5	Surface Area (S), mm^2	278.986±0.032
6	Arithmetic Mean Diameter (D_a)	11.060±0.2697
7	Geometric Mean Diameter (D_g)	10.248±0.3407
8	Equivalent Diameter (D_e)	10.634±0.2994
9	Sphericity (ϕ)	0.593±0.0014
10	Shape Factor (Z)	0.570±0.0135
11	Bulk Density kg/m^3	0.537±0.01117
12	Solid Density kg/m3	0.987
13	Porosity, %	45.59

4.1.2 RESULTS OF DRYING CHARACTERISTICS OF GROUNDNUTS

4.1.2.1. DRYING CURVES

The drying curves when the moisture content was plotted against the drying duration for the different temperatures and air velocities are shown in figure 4.1 to 4.3

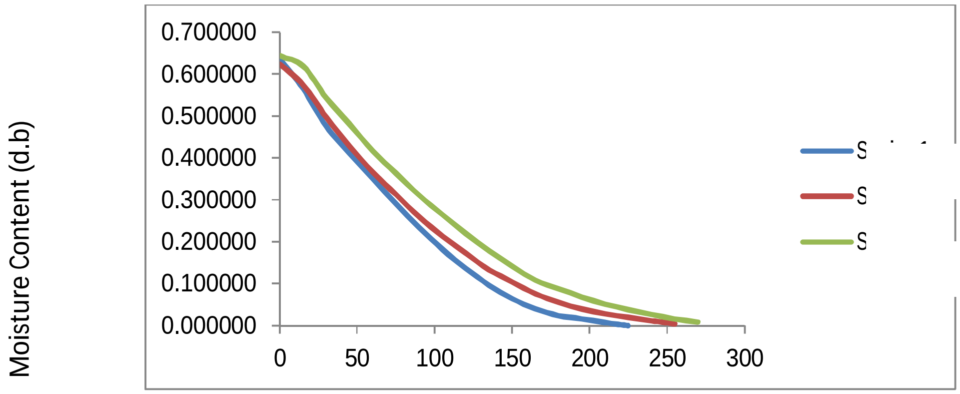


Fig 4.1: Moisture content against time at air velocity of 0.6 m/s.

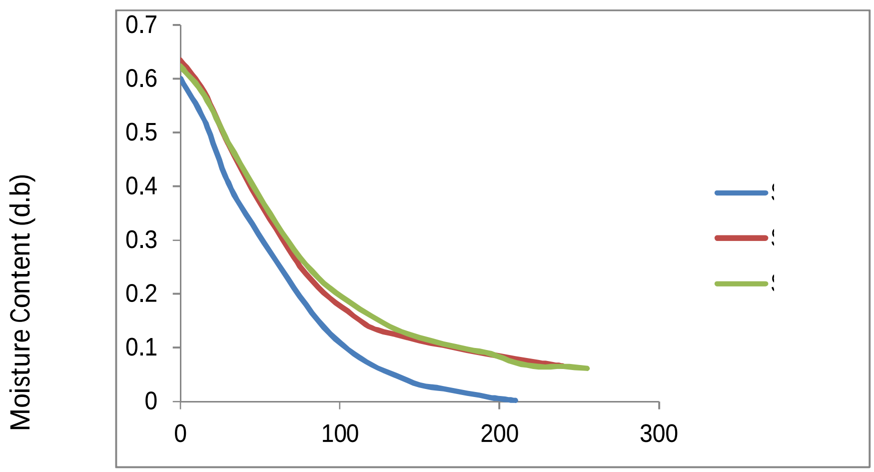


Fig 4.2: Moisture content against time at air velocity of 1.0 m/s.

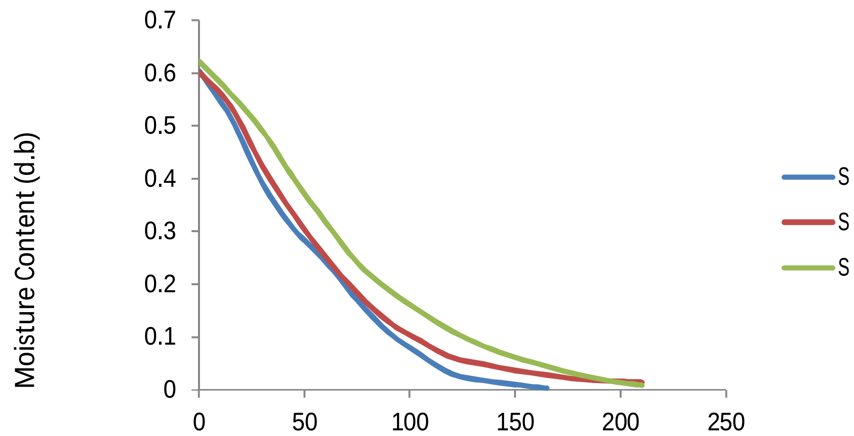


Fig 4.3: Moisture content against time at air velocity of 1.5 m/s.

4.1.2.2. RESULTS FOR DRYING RATE (D_r) CURVES

Figures 4.4 to 4.6 show graphs of drying rates against time

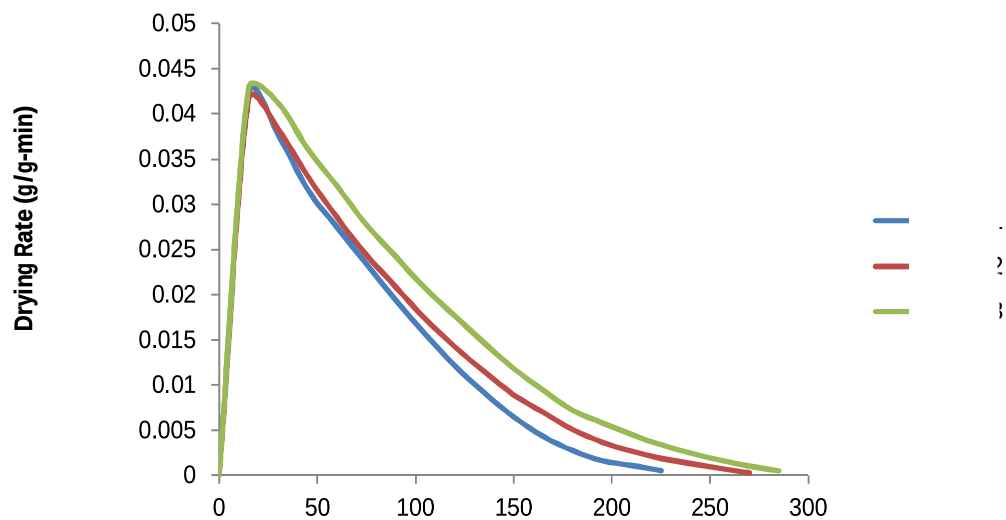


Figure 4.4: A graph of drying rate against time at different temperatures at 0.6m/s air velocity

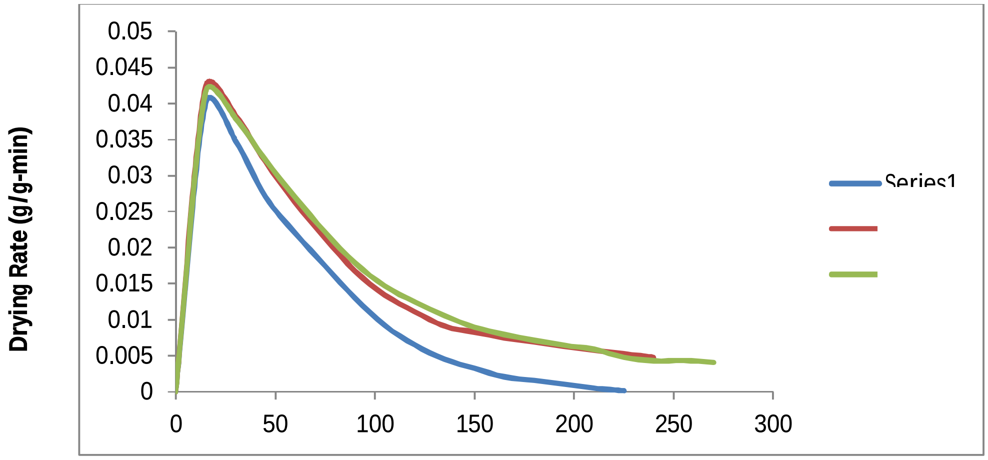


Fig 4.5: A graph of drying rate against time at different temperatures at 1.0 m/s air velocity

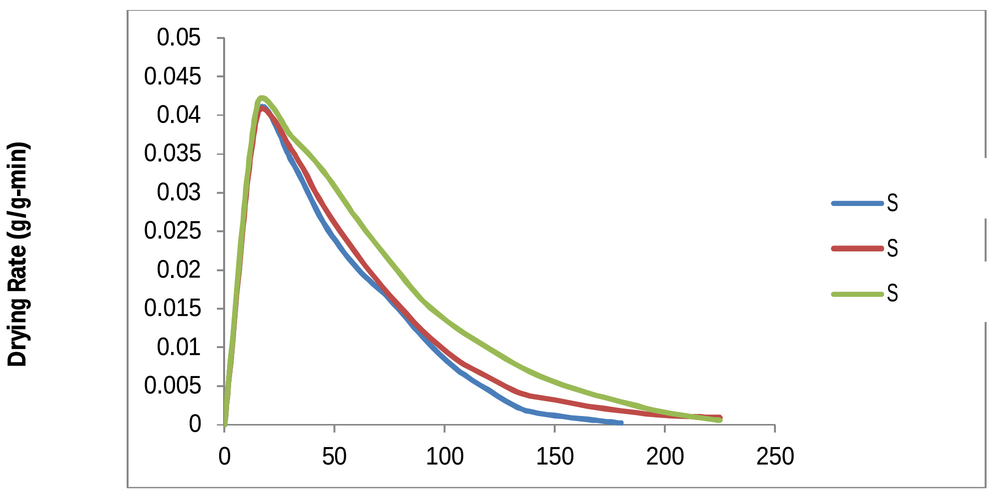


Figure 4.6: A graph of drying rate against time at different temperatures at 1.5 m/s air velocity

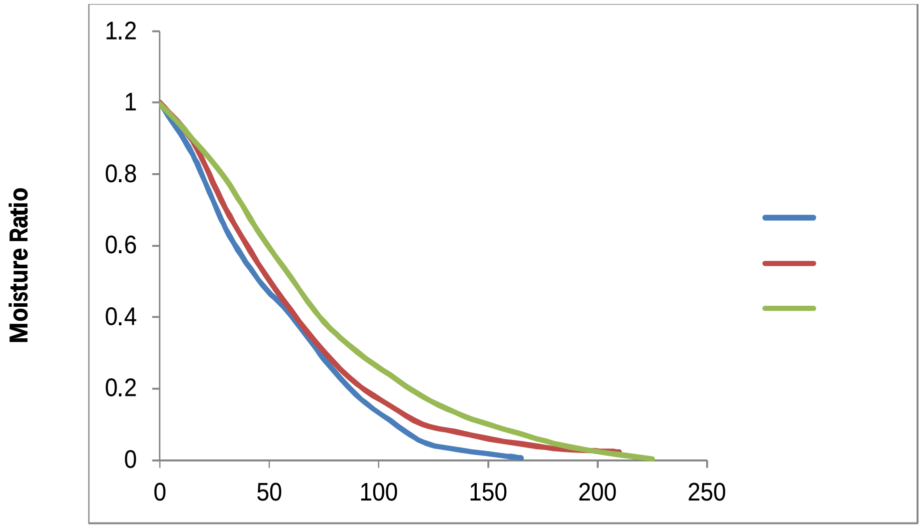


Fig 4.7: Moisture ratio against drying time at various temperatures and air velocity of 0.6m/s

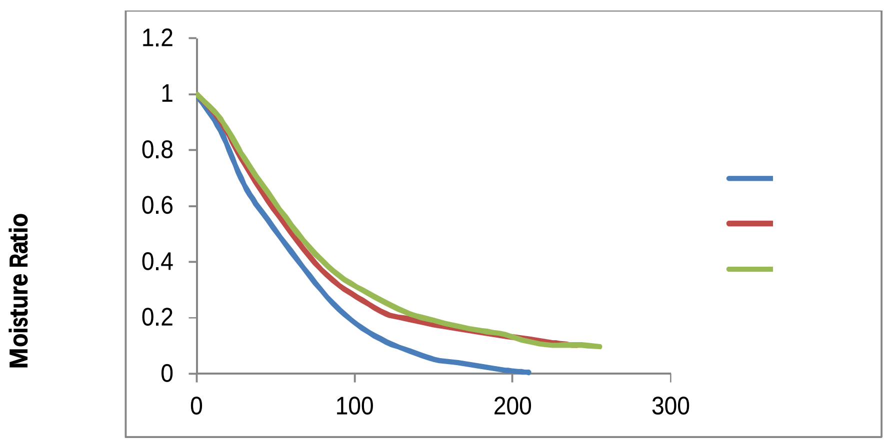


Fig 4.8: Moisture ratio against drying time at various temperatures and air velocity of 1.0m/s

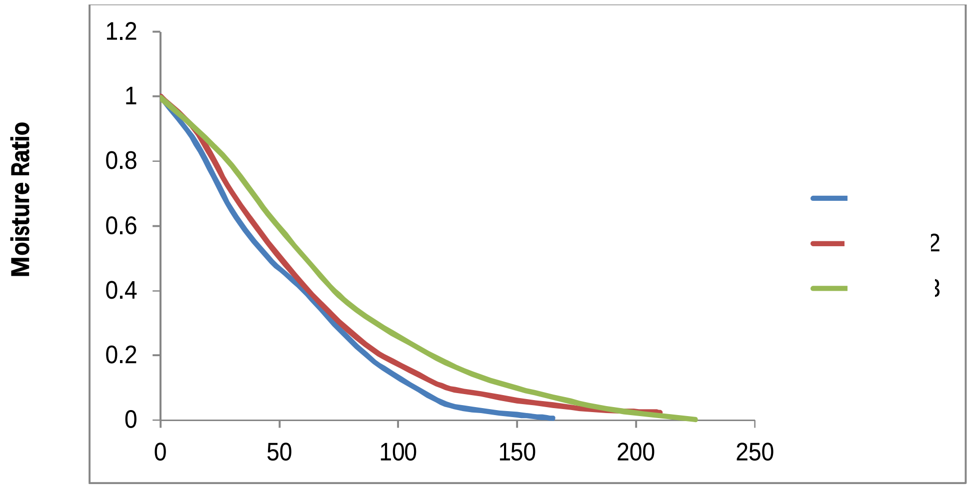


Fig 4.9: Moisture ratio against drying time at various temperatures and air velocity of 1.5m/s

4.1.2.3. DRYING RATE CONSTANTS (K)

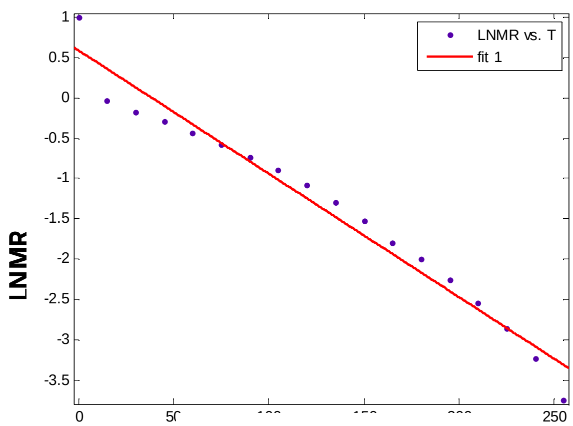


Fig 4.10: Log of moisture ratio against drying time at 45^{o}C at 0.6m/s air velocity.

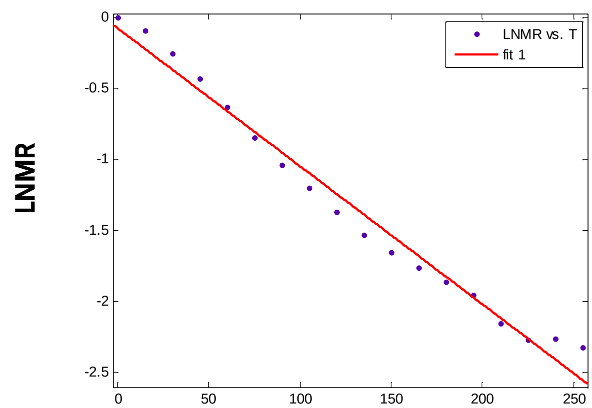
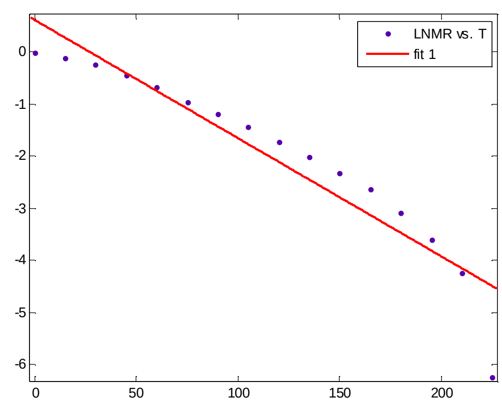


Fig 4.11: Log of moisture ratio against drying time at 45°C at 1.0m/s air velocity.



T(mins)

Fig 4.12: Log of moisture ratio against drying time at 45°C at 1.5 m/s air velocity.

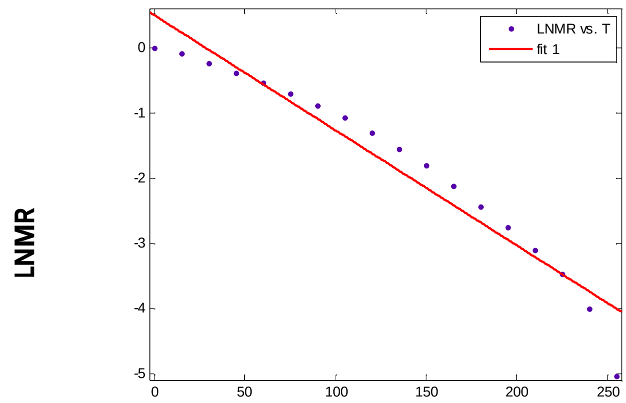


Fig 4.13: Log of moisture ratio against drying time at 55^{o}C at 0.6m/s air velocity.

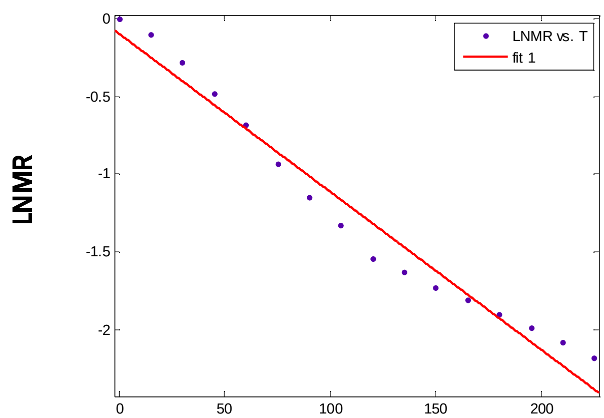


Fig 4.14: Log of moisture ratio against drying time at 55^{o}C at 1.0m/s air velocity

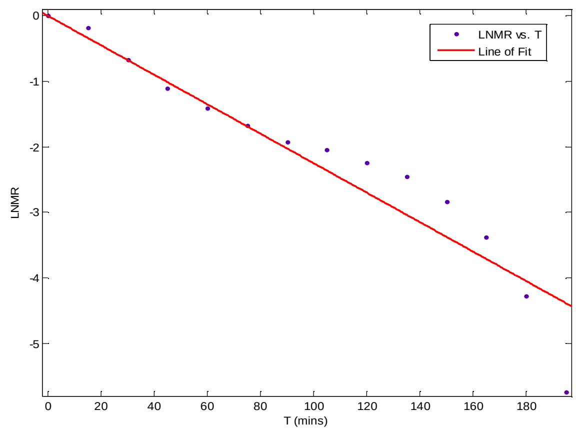


Fig 4.15: Log of moisture ratio against drying time at 55^oC at 1.5 m/s air velocity

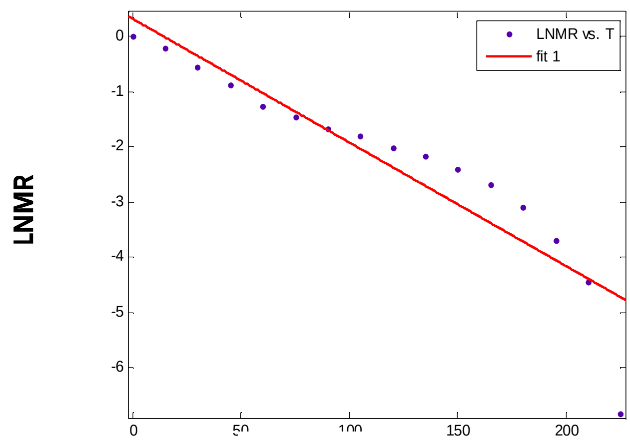


Figure 4.16: Log of moisture ratio against drying time at 65^oC at 0.6 m/s air velocity

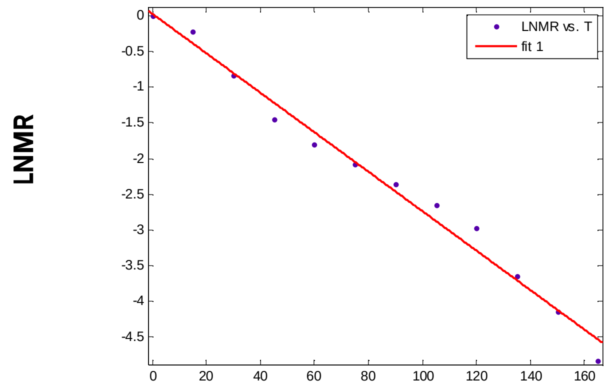


Figure 4.17: Log of moisture ratio against drying time at 65^{o}C at 1.0 m/s air velocity

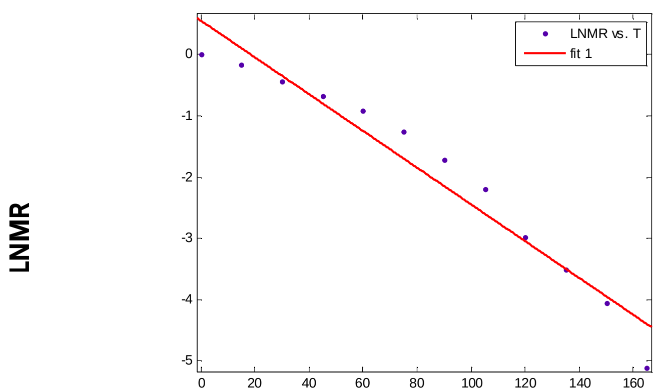


Figure 4.18: Log of moisture ratio against drying time at 65^{o}C at 1.5 m/s air velocity

Figure 4.19 shows gragh of drying rate duration against temperature of the drying medium

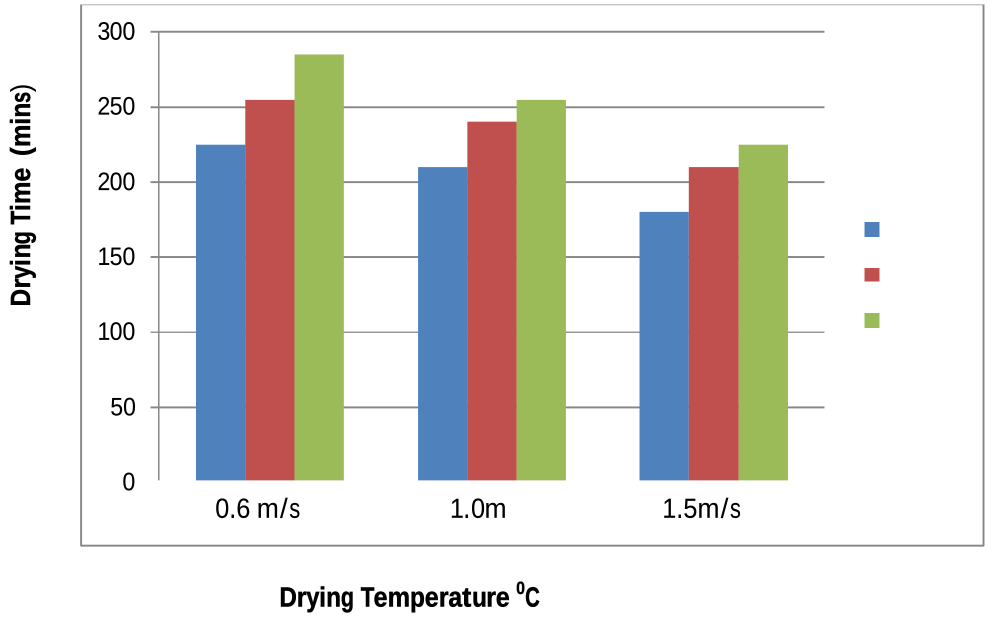


Fig 4.19: Graph of drying duration against temperature of the drying medium

4.1.3 MATHEMATICAL MODELLING OF DRYING CURVES

The drying data obtained (moisture ratio against drying time) for the three temperature samples and varying air velocities, were fitted into the five thin layer models (table 3.2). The curve fittings are presented from figure 4.20 to 4.64, while the model parameters are presented in tables 4.3, 4.4 and 4.5.

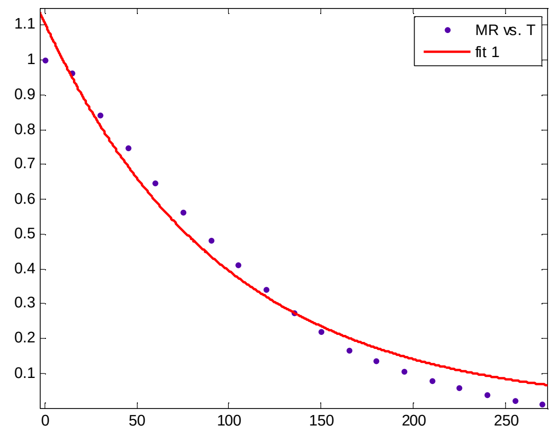


Fig 4.20: Henderson andPabis model curve fitting for 45^{0}C and 0.6m/s air velocity

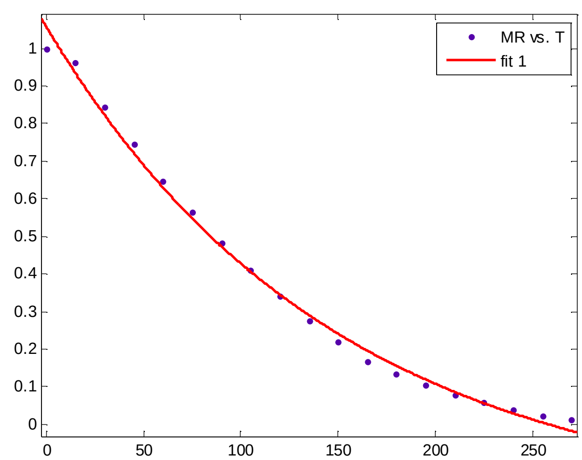


Fig 4.21: Logarithmic model curve fitting for 45^{0}C and 0.6m/s air velocity

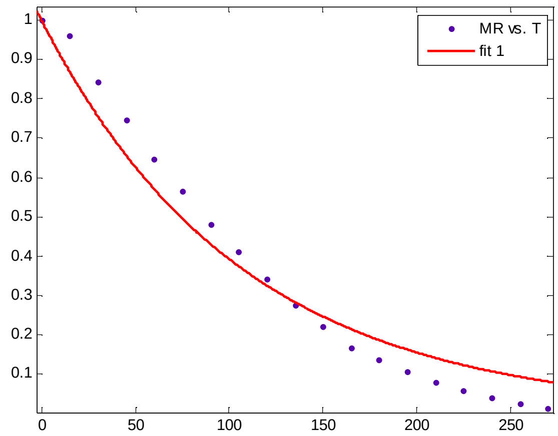


Fig 4.22: Newton model curve fitting for 45^{0}C and 0.6m/s air velocity

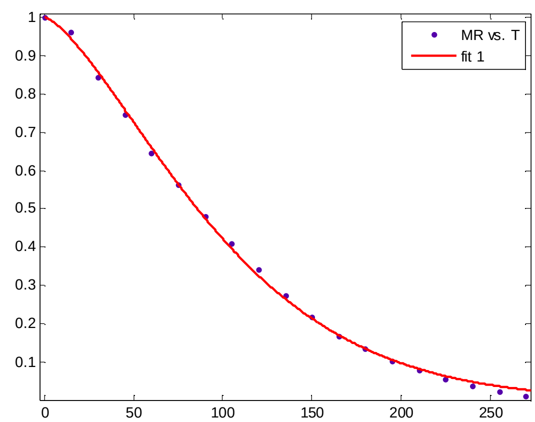


Fig 4.23: Page model curve fitting for 45^{0}C and 0.6m/s air velocity

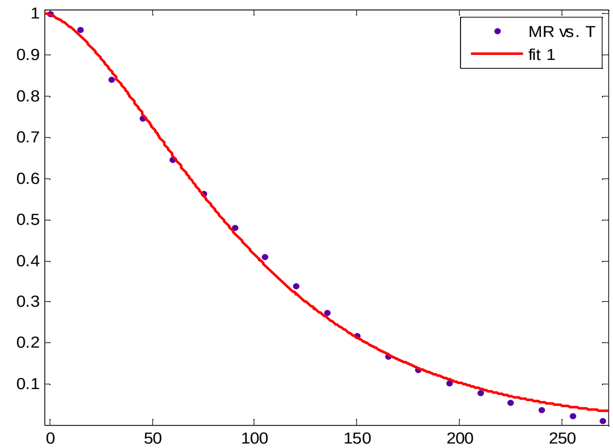


Fig 4.24: Two-term model curve fitting for 45^{0}C and 0.6m/s air velocity

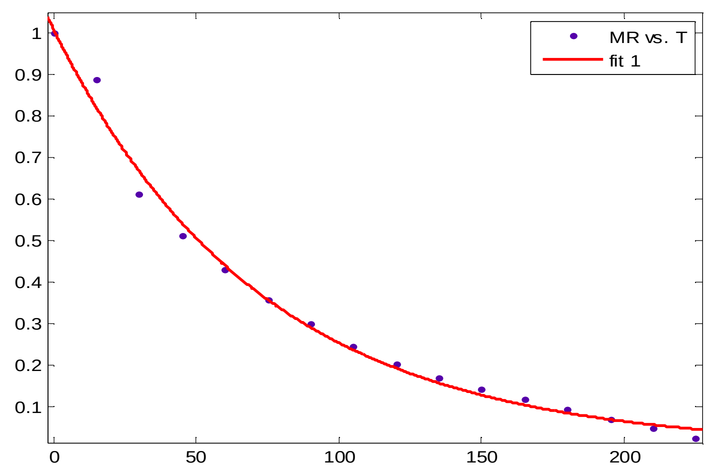


Fig 4.25: Henderson andPabis model curve fitting for 45^{0}C and 1.0 m/s air velocity

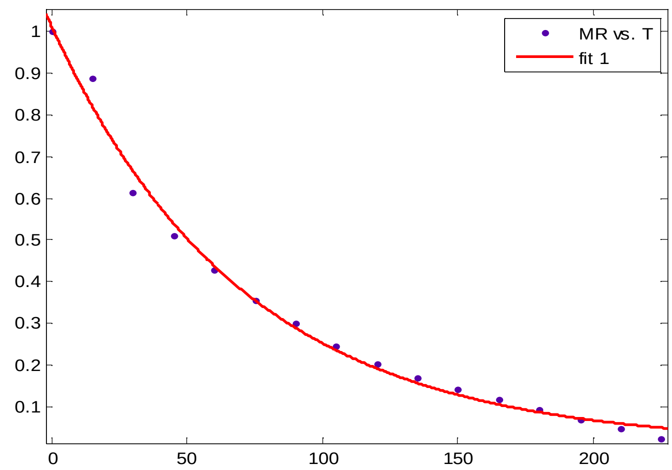


Fig 4.26: Logarithmic model curve fitting for 45^{0}C and 1.0 m/s air velocity

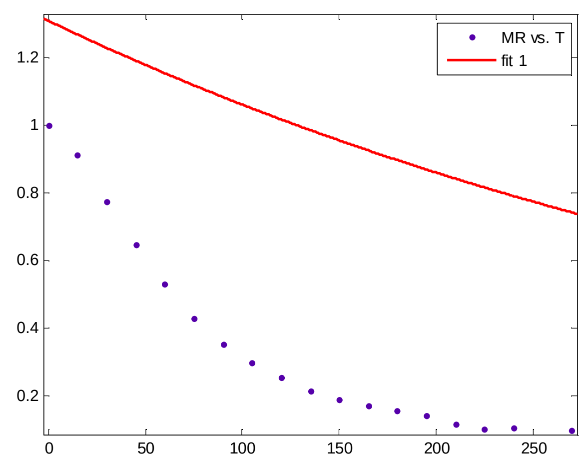


Fig 4.27: Newton model curve fitting for 55^{0}C and 1.0 m/s air velocity

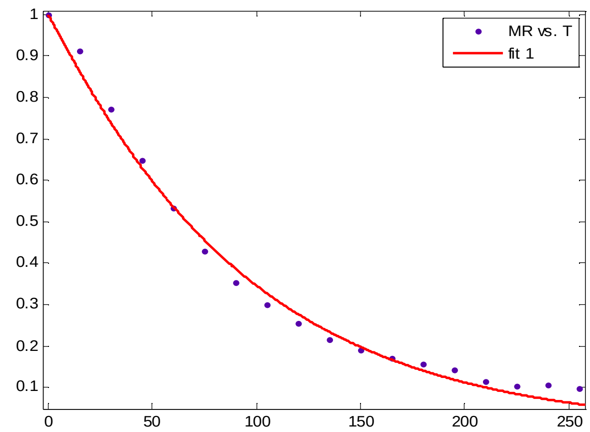


Fig 4.28: Page model curve fitting for 45^{0}C and 1.0 m/s air velocity

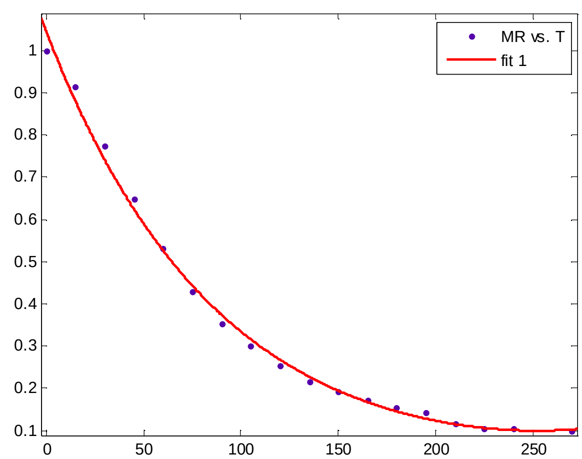


Fig 4.29: Two term model curve fitting for 45^{0}C and 1.0 m/s air velocity

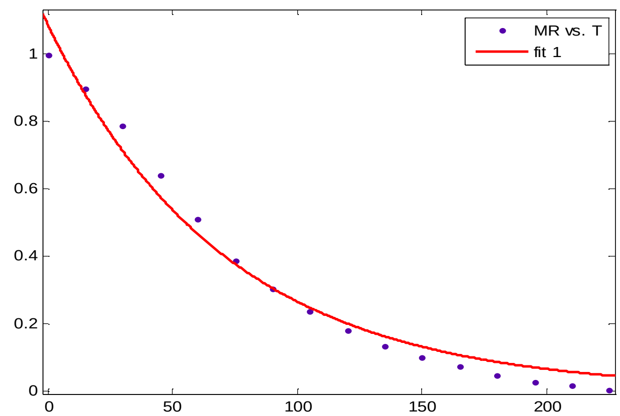


Fig 4.30: Henderson andPabis model curve fitting for 45^{0}C and 1.5 m/s air velocity

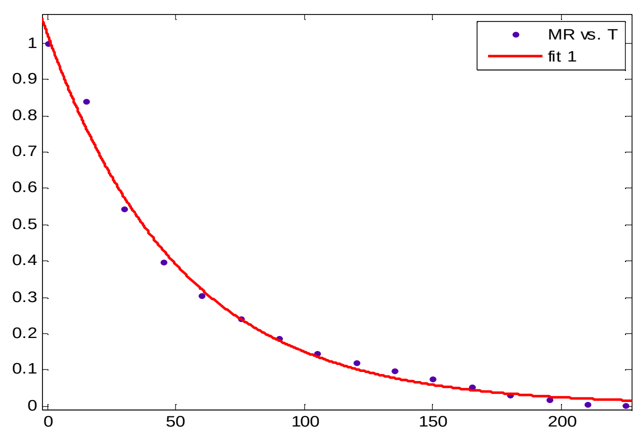


Fig 4.31: Logarithmic model curve fitting for 45^{0}C and 1.5 m/s air velocity

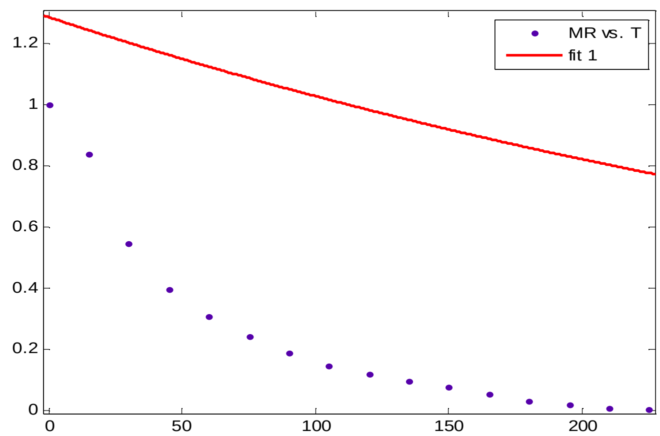


Fig 4.32: Newton model curve fitting for 45^{0}C and 1.5 m/s air velocity

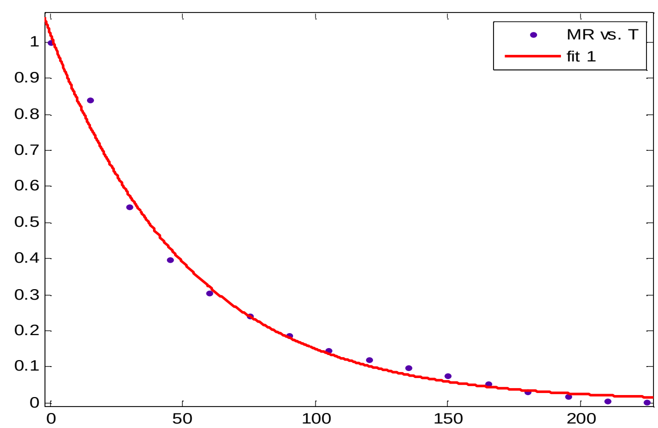


Fig 4.33: Page model curve fitting for 45^{0}C and 1.5 m/s air velocity

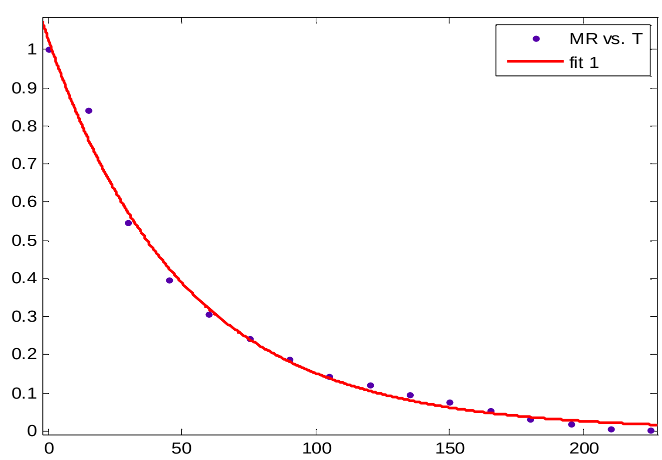


Fig 4.34: Two-term model curve fitting for 45^{0}C and 1.5 m/s air velocity

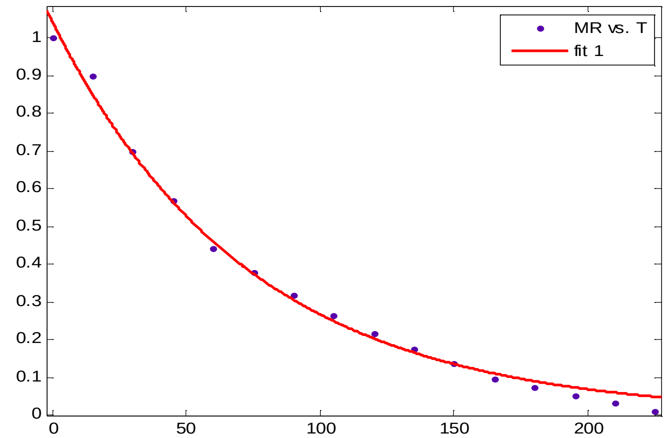


Fig 4.35: Henderson andPabis model curve fitting for 55^{0}C and 0.6 m/s air velocity

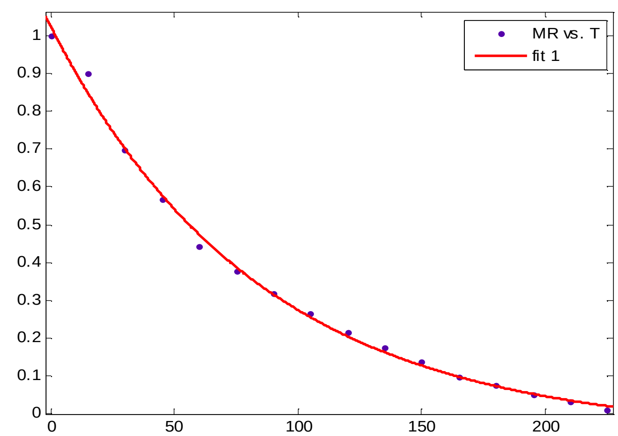


Fig 4.36: Logarithmic model curve fitting for 55^{0}C and 0.6 m/s air velocity

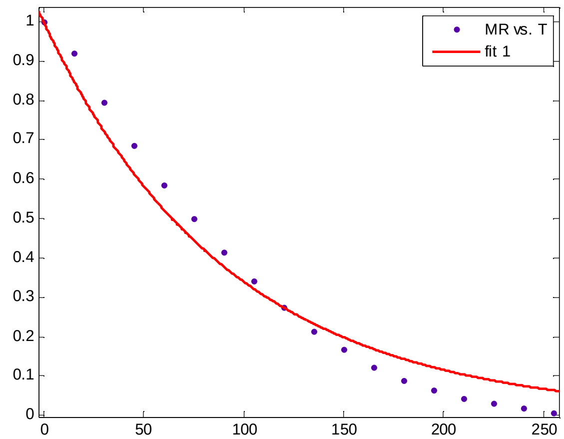


Fig 4.37: Newton model curve fitting for 55^{0}C and 0.6 m/s air velocity

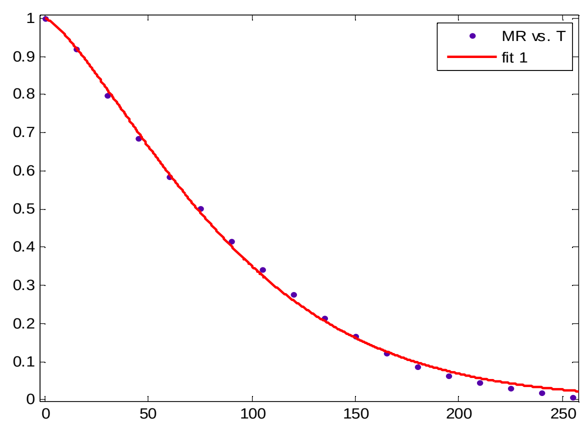


Fig 4.38: Pagemodel curve fitting for 55^{0}C and 0.6 m/s air velocity

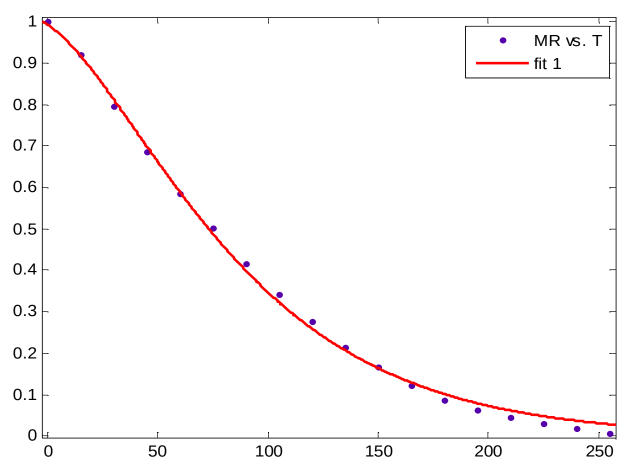


Fig 4.39: Two-term model curve fitting for 55^{0}C and 0.6 m/s air velocity

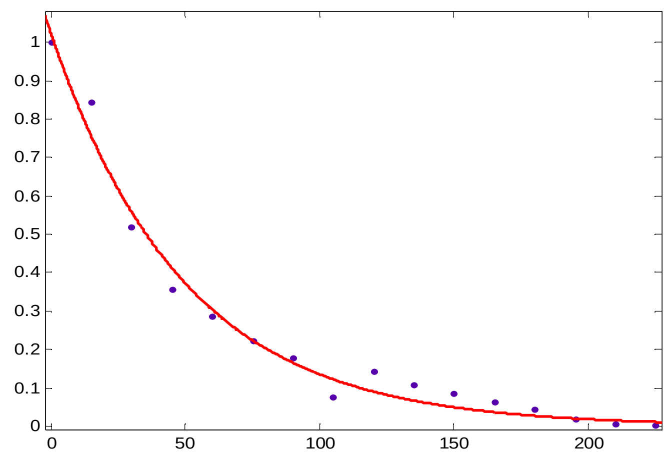


Fig 4.40: Henderson andPabis model curve fitting for 55^{0}C and 1.0 m/s air velocity

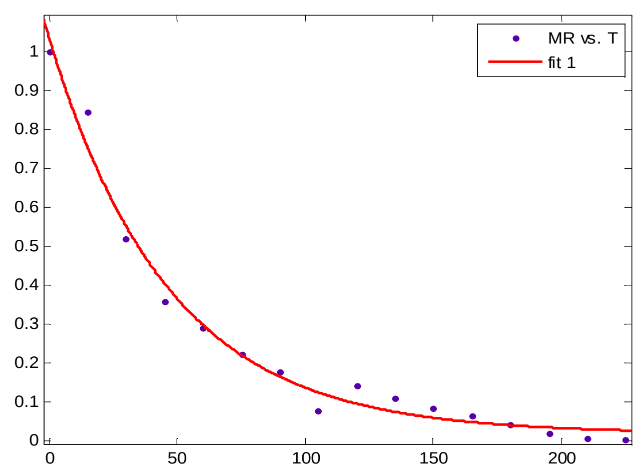


Fig 4.41: Logarithmic model curve fitting for 55^{0}C and 1.0 m/s air velocity

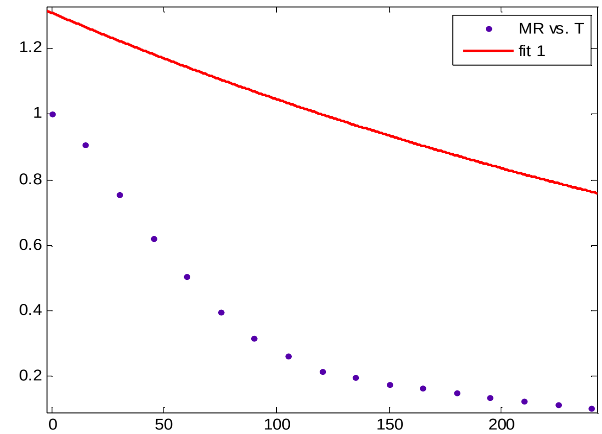


Fig 4.42: Newton model curve fitting for 55^{0}C and 1.0 m/s air velocity

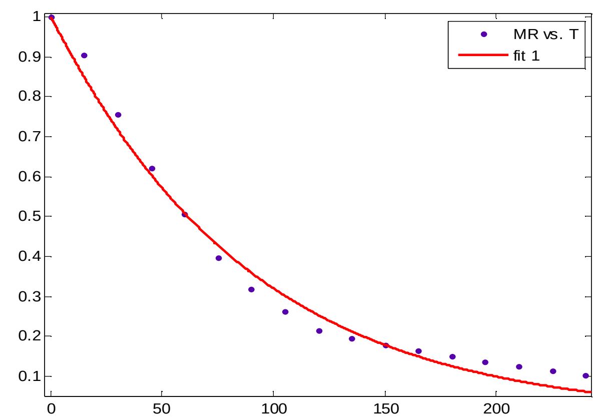


Fig 4.43: Page model curve fitting for 55^{0}C and 1.0 m/s air velocity

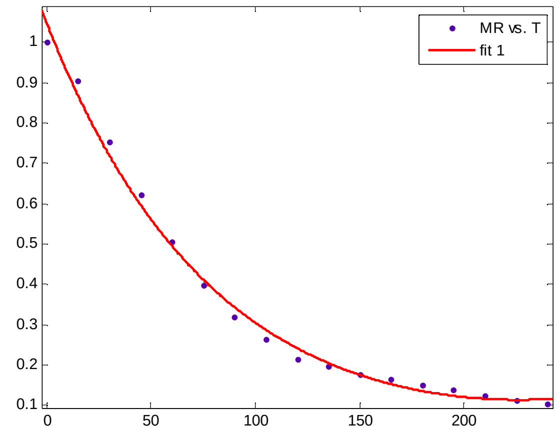


Fig 4.44: Two term model curve fitting for 55^{0}C and 1.0 m/s air velocity

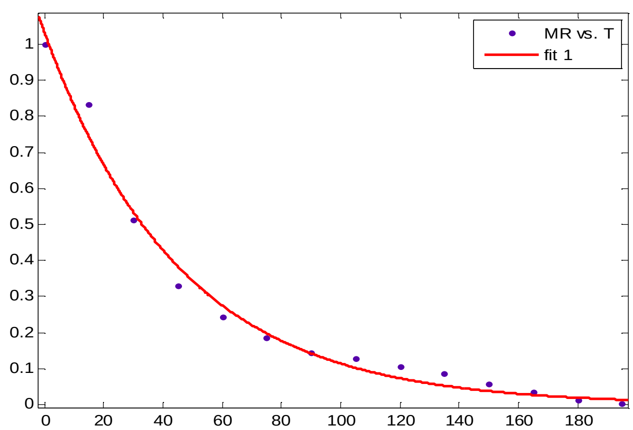


Fig 4.45: Henderson andPabis model curve fitting for 55^{0}C and 1.5 m/s air velocity

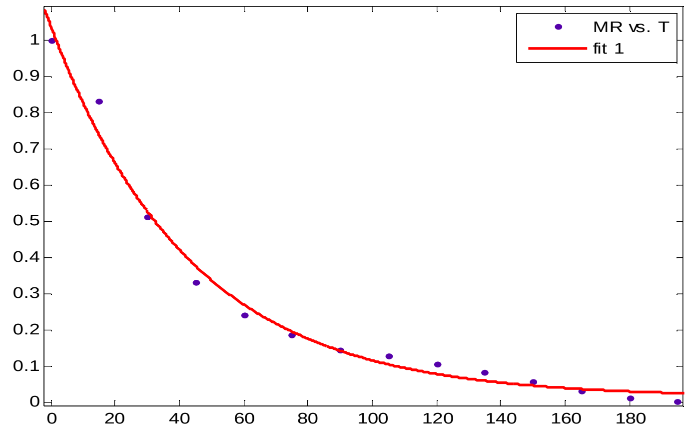


Fig 4.46: Logarithmic model curve fitting for 55^{0}C and 1.5 m/s air velocity

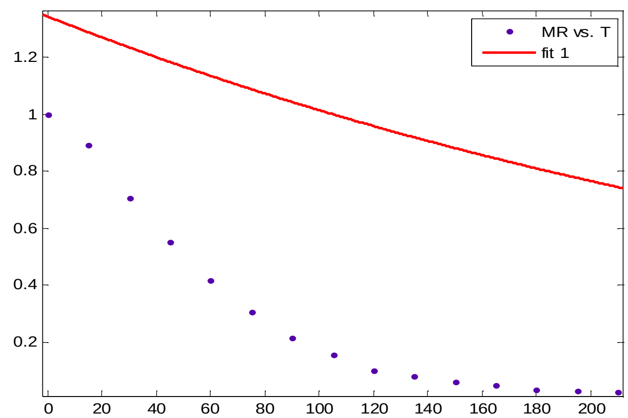


Fig 4.47: Newton model curve fitting for 55^{0}C and 1.5 m/s air velocity

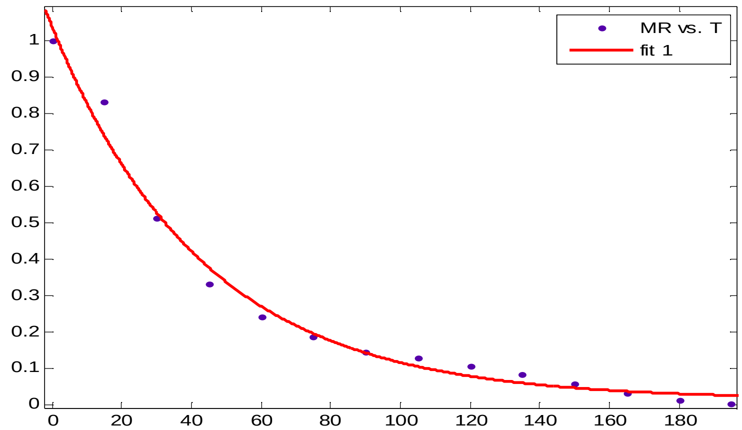


Fig 4.48: Page model curve fitting for 55^{0}C and 1.5 m/s air velocity

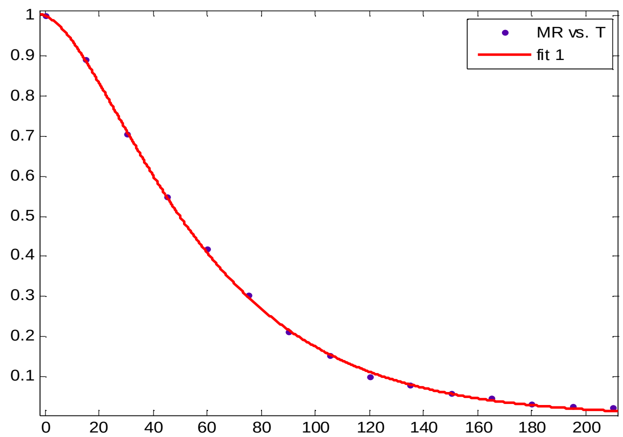


Fig 4.49: Two term model curve fitting for 55^{0}C and 1.5 m/s air velocity

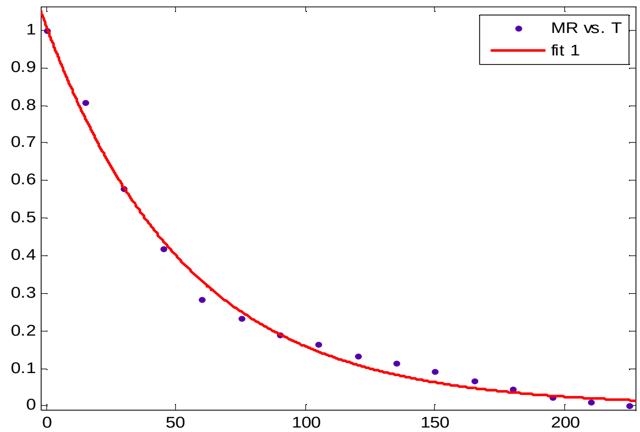


Fig 4.50: Henderson andPabis model curve fitting for 65^{0}C and 0.6 m/s air velocity

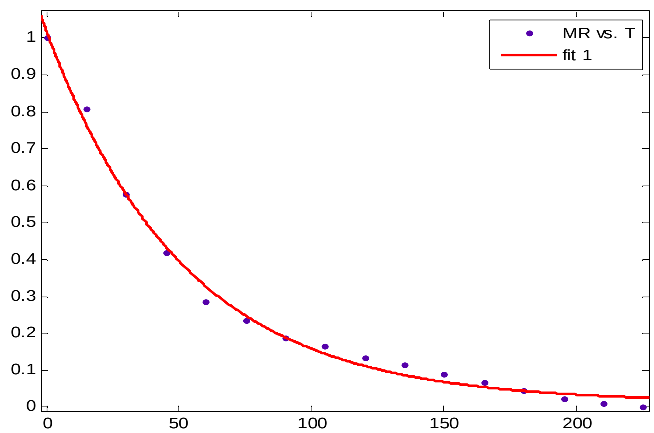


Fig 4.51: Logarithmic model curve fitting for 65^{0}C and 0.6 m/s air velocity

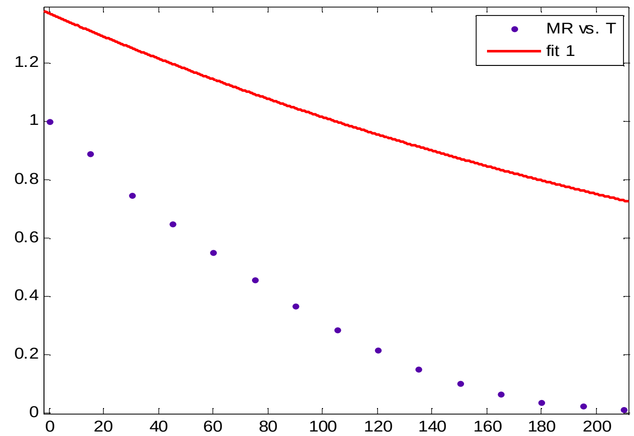


Fig 4.52: Newton model curve fitting for 65^0C and 0.6 m/s air velocity

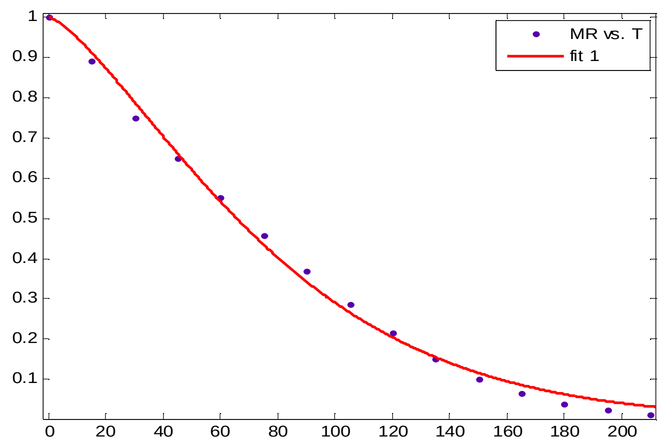


Fig 4.53: Page model curve fitting for 65^0C and 0.6 m/s air velocity

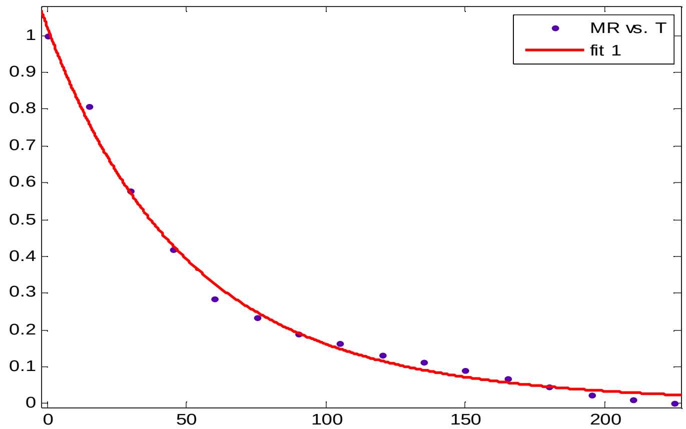


Fig 4.54: Two term model curve fitting for 65^{0}C and 0.6 m/s air velocity

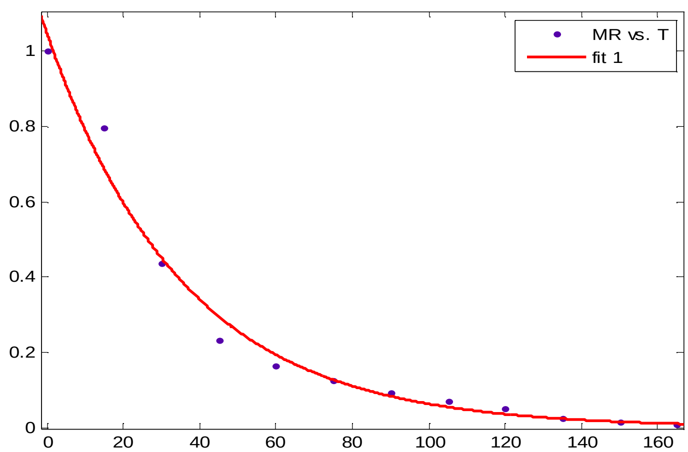


Fig 4.55: Henderson andPabis model curve fitting for 65^{0}C and 1.0 m/s air velocity

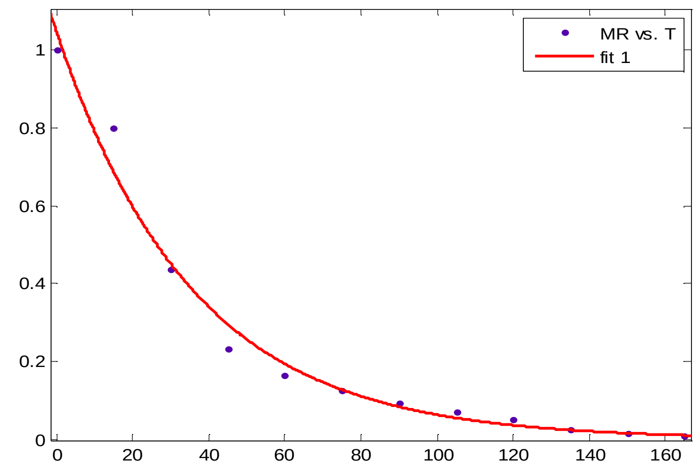


Fig 4.56: Logarithmic model curve fitting for 65^{0}C and 1.0 m/s air velocity

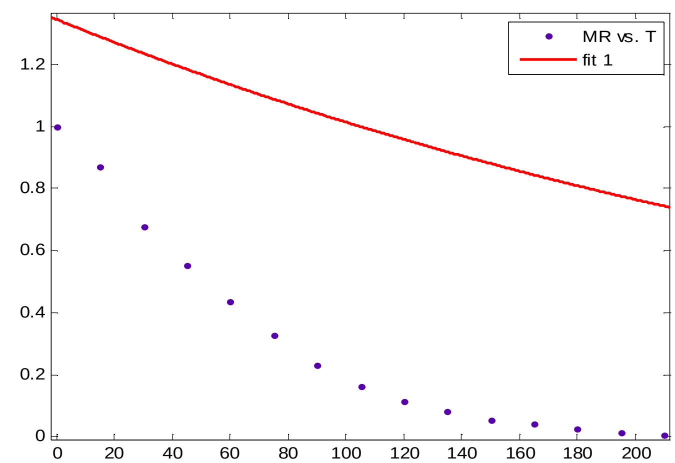


Fig 4.57: Newton model curve fitting for 65^{0}C and 1.0 m/s air velocity

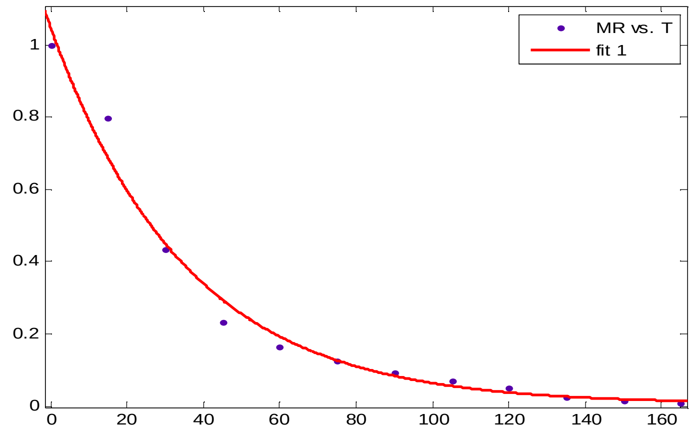


Fig **4.58: Page model curve fitting for 65^{0}C and 1.0 m/s air velocity**

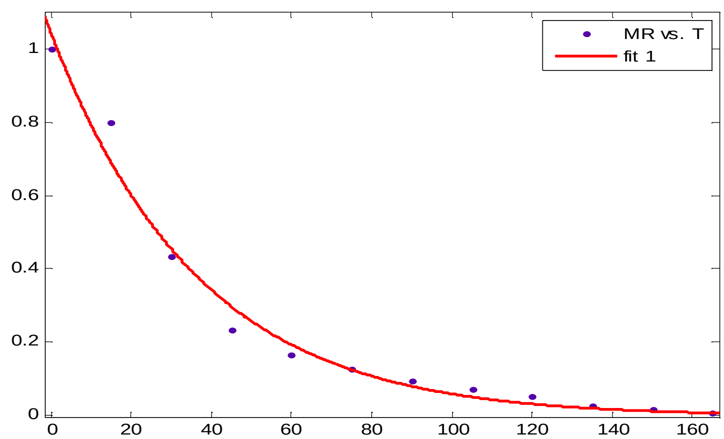


Fig 4.59: Two term model curve fitting for 65^{0}C and 1.0 m/s air velocity

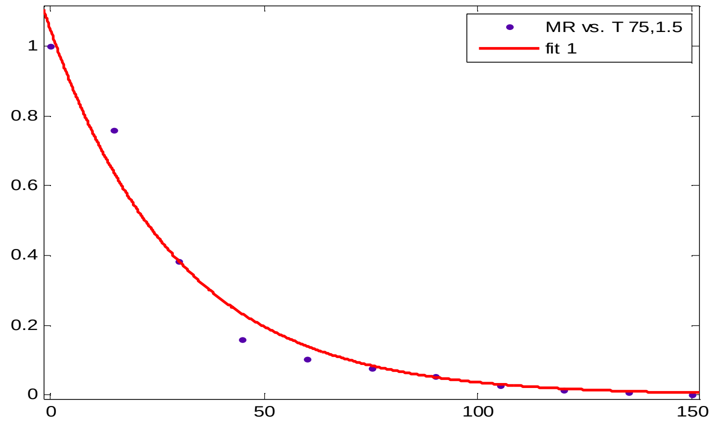


Fig 4.60: Henderson andPabis model curve fitting for 65^{0}C and 1.5 m/s air velocity

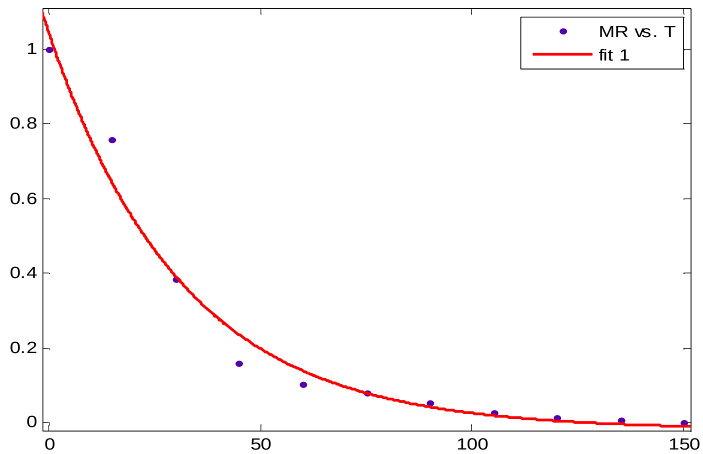


Fig 4.61: Logarithmic model curve fitting for 65^{0}C and 1.5 m/s air velocity

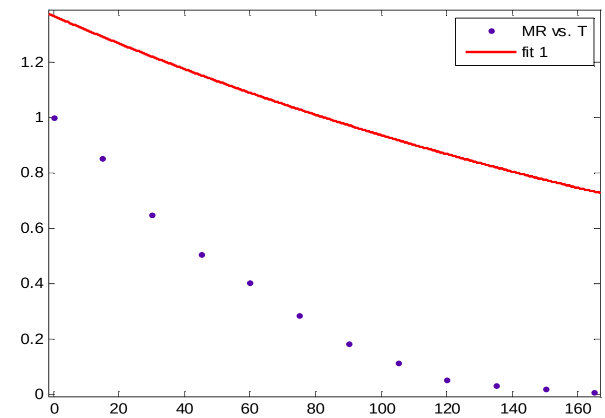


Fig 4.62: Newton model curve fitting for 65^{0}C and 1.5 m/s air velocity

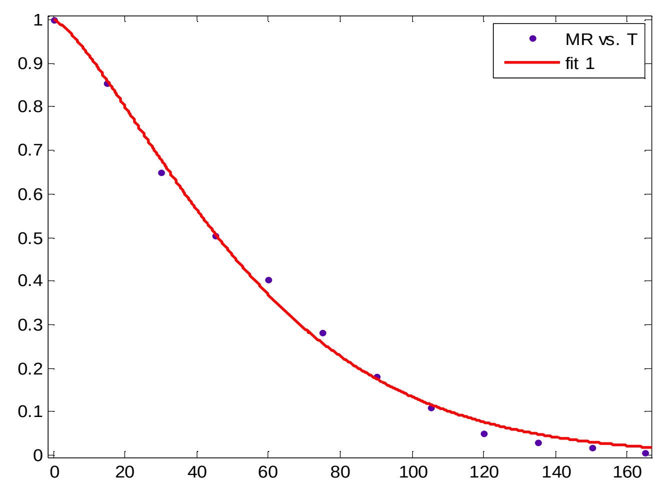


Fig 4.63: Page model curve fitting for 65^{0}C and 1.5 m/s air velocity

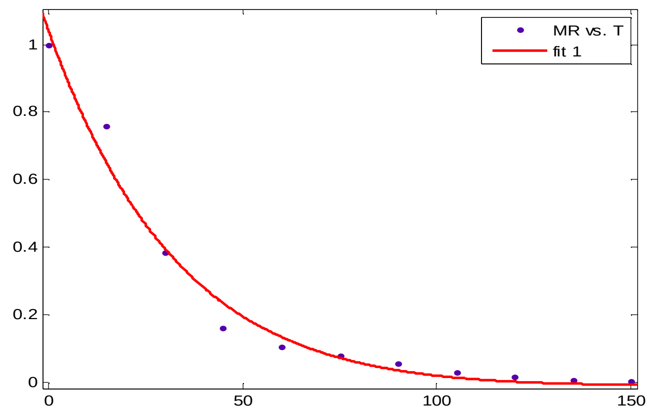


Fig 4.64: Two term model curve fitting for 65^{0}C and 1.5 m/s air velocity

Table 4.2: Model parameters for the groundnut seeds at air flow rate of 0.6 m/s

Temp. (^oC)	**Mod No.**	**Model Expression**	**MODEL PARAMETERS**							**GOODNESS OF FIT**		
			A	K	K_1	K_2	B	n	C	R^2	SSE	RMSE
45	1	$MR = \exp(-k * t)$	-	0.00934	-	-	-	-	-	0.9649	0.06941	0.0621
	2	$MR = \exp(-k * t)^n$	-	0.00119	-	-	-	1.43	-	0.999	0.00204	0.01095
	3	$MR = A * \exp(-k * t)$	1.107	-0.0103	-	-	-	-	-	0.9782	0.04317	0.05039
	4	$MR = A * \exp(-k * t) + c$	1.282	0.006747	-	-	-	-	-0.2244	0.9953	0.009274	0.02408
	5	$MR = A * \exp(-k_1 * t) + B * \exp(-k_2 * t)$	-1172	-	-1.581	-1.581	1172	-	-	0.9981	0.003765	0.01584
55	1	$MR = \exp(-k * t)$	-	0.01077	-	-	-	-	-	0.9741	0.04728	0.05274
	2	$MR = \exp(-k * t)^n$	-	0.002031	-	-	-	1.356	-	0.9987	0.002373	0.01218
	3	$MR = A * \exp(-k * t)$	1.084	-0.01163	-	-	-	-	-	0.9823	0.03228	0.04492
	4	$MR = A * \exp(-k * t) + c$	1.213	0.008152	-	-	-	-	-0.1721	0.9967	0.006053	0.02009
	5	$MMR = A * \exp(-k_1 * t) + B * \exp(-k_2 * t)$	-198.5	-	-1.639	-1.638	198.7	-	-	0.9981	0.003497	0.0158
65	1	$MR = \exp(-k * t)$	-	0.2017	-	-	-	-	-	-3.274	6.545	0.6837
	2	$MR = \exp(-k * t)^n$	-	0.002271	-	-	-	1.368	-	0.996	0.006168	0.02178
	3	$MR = A * \exp(-k * t)$	1.073	-0.01297	-	-	-	-	-	0.977	0.03519	0.05203
	4	$MR = A * \exp(-k * t) + c$	0.5496	0.5404	-	-	-	-	-0.2567	0.997	0.004657	0.0197
	5	$MR = A * \exp(-k_1 * t) + B * \exp(-k_2 * t)$	0.8454	-	-0.007695	-0.007695	0	-	-	0.845	0.2373	0.1469

Table 4.3: Model parameters for the groundnut seeds at air flow rate of 1.0 m/s

Temp. (^oC)	**Mod No.**	**Model Expression**		**MODEL PARAMETERS**						**GOODNESS OF FIT**		
			A	K	K_1	K_2	B	n	C	R^2	SSE	RMSE
45	1	$MR = \exp(-k * t)$	-	0.01062	-	-	-	-	-	0.9915	0.01231	0.02691
	2	$MR = \exp(-k * t)^n$	-	0.008579	-	-	-	1.046	-	0.9922	0.01135	0.02663
	3	$MR = A * \exp(-k * t)$	1.034	-0.011	-	-	-	-	-	0.9931	0.01002	0.02502
	4	$MR = A * \exp(-k * t) + c$	0.2119	0.9807	-	-	-	-	0.03913	0.9947	0.007664	0.0226
	5	$MR = A * \exp(-k_1 * t) + B * \exp(-k_2 * t)$	1.045	-	-0.01146	0.01818	0.0004511	-	-	0.9956	0.006399	0.02138
55	1	$MR = \exp(-k * t)$	-	0.1702	-	-	-	-	-	-4.56	7.568	0.6878
	2	$MR = \exp(-k * t)^n$	-	0.01025	-	-	-	1.023	-	0.9873	0.01731	0.03397
	3	$MR = A * \exp(-k * t)$	1.03	-0.01174	-	-	-	-	-	0.9884	0.01583	0.03248
	4	$MR = A * \exp(-k * t) + c$	0.1901	1.045	-	-	-	-	0.05736	0.9923	0.01047	0.02735
	5	$MR = A * \exp(-k_1 * t) + B * \exp(-k_2 * t)$	1.046	-	-0.01262	0.01442	0.002022	-	-	0.9937	0.008623	0.02575
65	1	$MR = \exp(-k * t)$	-	0.1895	-	-	-	-	-	-4.22	7.932	0.7527
	2	$MR = \exp(-k * t)^n$	-	0.01110	-	-	-	1.021	-	0.9887	0.02146	0.04279
	3	$MR = A * \exp(-k * t)$	1.065	-0.01652	-	-	-	-	-	0.988	0.0182	0.03741
	4	$MR = A * \exp(-k * t) + c$	0.2739	0.9022	-	-	-	-	-0.08488	0.9954	0.006963	0.02409
	5	$MR = A * \exp(-k_1 * t) + B * \exp(-k_2 * t)$	1.249	-	-0.02975	-0.02975	0	-	-	0.8178	0.2769	0.1587

Table 4.4: Model parameters for the groundnut seeds at air flow rate of 1.5m/s

Temp. (^{o}C)	**Mod No.**	**Model Expression**		**MODEL PARAMETERS**						**GOODNESS OF FIT**		
			A	K	K_1	K_2	B	n	C	R^2	SSE	RMSE
45	1	$MR = \exp(-k*t)$	-	0.1969	-	-	-	-	-	-3.667	7.843	0.7231
	2	$MR = \exp(-k*t)^{n}$	-	0.002998	-	-	-	1.521	-	0.9932	0.003488	0.04352
	3	$MR = A*\exp(-k*t)$	1.087	-0.01409	-	-	-	-	-	0.9817	0.03067	0.04681
	4	$MR = A*\exp(-k*t) + c$	0.3597	0.7558	-	-	-	-	-0.1308	0.9933	0.01134	0.02953
	5	$MR = A*\exp(-k_1*t) + B*\exp(-k_2*t)$	0	-	- 0.01258	- 0.01258	1.037	-	-	0.9749	0.04225	0.05934
55	1	$MR = \exp(-k*t)$	-	0.1888	-	-	-	-	-	-4.142	7.93	0.7526
	2	$MR = \exp(-k*t)^{n}$	-	0.003443	-	-	-	1.413	-	0.9943	0.003892	0.02342
	3	$MR = A*\exp(-k*t)$	1.079	-0.01681	-	-	-	-	-	0.9866	0.02069	0.0399
	4	$MR = A*\exp(-k*t) + c$	1.121	0.01445	-	-	-	-	- 0.06155	0.991	0.01381	0.03392
	5	$MR = A*\exp(-k_1*t) + B*\exp(-k_2*t)$	1.721	-	- 0.02257	- 0.05025	-0.72	-	-	0.9996	0.000561	0.007142
65	1	$MR = \exp(-k*t)$	-	0.2049	-	-	-	-	-	-3.426	5.769	0.7242
	2	$MR = \exp(-k*t)^{n}$	-	0.003777	-	-	-	1.362	-	0.9968	0.004207	0.02051
	3	$MR = A*\exp(-k*t)$	1.067	-0.01852	-	-	-	-	-	0.9795	0.02673	0.05171
	4	$MR = A*\exp(-k*t) + c$	0.4094	0.7049	-	-	-	-	-0.1684	0.9949	0.006594	0.02707
	5	$MR = A*\exp(-k_1*t) + B*\exp(-k_2*t)$	1.185	-	- 0.02611	- 0.02611	0	-	-	0.9146	0.1113	0.118

Table 4.5: Statistical results obtained from the selected models for air velocity of 0.6 m/s

T^0C	Model Name	R^2	SSE	RMSE
45	Newton	0.9649	0.06941	0.0621
	Page	0.999	0.00204	0.01095
	Henderson and Pabis	0.9782	0.04317	0.05039
	Logarithmic	0.9953	0.009274	0.02408
	Two-term	0.9981	0.003765	0.01584
55	Newton	0.9741	0.04728	0.05274
	Page	0.9987	0.002373	0.01218
	Henderson and Pabis	0.9823	0.03228	0.04492
	Logarithmic	0.9967	0.006053	0.02009
	Two-term	0.9981	0.003497	0.0158
65	Newton	-3.274	6.545	0.6837
	Page	0.996	0.006168	0.02178
	Henderson and Pabis	0.977	0.03519	0.05203
	Logarithmic	0.997	0.004657	0.0197
	Two-term	0.845	0.2373	0.1469

Table 4.6: Statistical results obtained from the selected models for air velocity of 1.0 m/s

T^0C	**Model Name**	**R^2**	**SSE**	**RMSE**
45	Newton	0.9915	0.01231	0.02691
	Page	0.9922	0.01135	0.02663
	Henderson and Pabis	0.9931	0.01002	0.02502
	Logarithmic	0.9947	0.007664	0.0226
	Two-term	0.9956	0.006399	0.02138
55	Newton	-4.56	7.568	0.6878
	Page	0.9873	0.01731	0.03397
	Henderson and Pabis	0.9884	0.01583	0.03248
	Logarithmic	0.9923	0.01047	0.02735
	Two-term	0.9937	0.008623	0.02575
65	Newton	-4.22	7.932	0.7527
	Page	0.9887	0.02146	0.04279
	Henderson and Pabis	0.988	0.0182	0.03741
	Logarithmic	0.9954	0.006963	0.02409
	Two-term	0.8178	0.2769	0.1587

Table 4.7: Statistical results obtained from the selected models for air velocity of 1.5 m/s

T^0C	Model Name	R^2	SSE	RMSE
45	Newton	-3.667	7.843	0.7231
	Page	0.9932	0.003488	0.04352
	Henderson and Pabis	0.9817	0.03067	0.04681
	Logarithmic	0.9933	0.01134	0.02953
	Two-term	0.9749	0.04225	0.05934
55	Newton	-4.142	7.93	0.7526
	Page	0.9943	0.003892	0.02342
	Henderson and Pabis	0.9866	0.02069	0.0399
	Logarithmic	0.991	0.01381	0.03392
	Two-term	0.9996	0.000561	0.007142
65	Newton	-3.426	5.769	0.7242
	Page	0.9968	0.004207	0.02051
	Henderson and Pabis	0.9795	0.02673	0.05171
	Logarithmic	0.9949	0.006594	0.02707
	Two-term	0.9146	0.1113	0.118

4.1.4 EFFECT OF TEMPERATURE ON THE DRYING RATE CONSTANT.

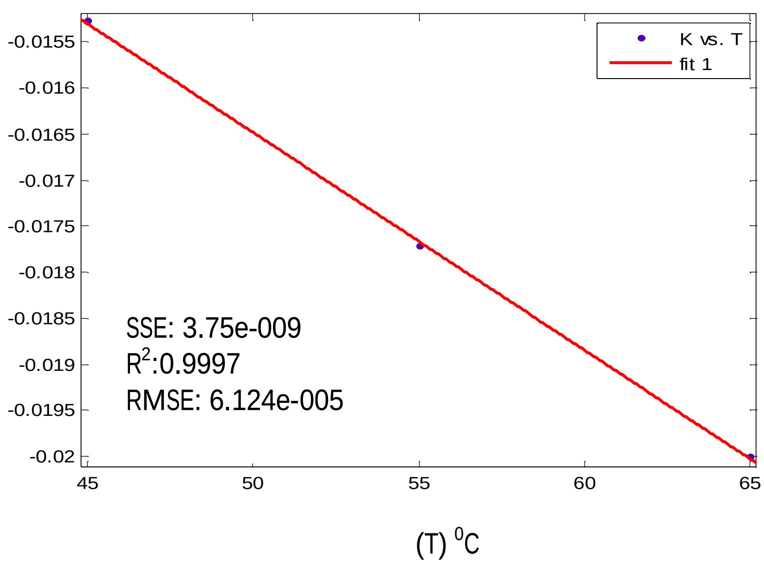


Fig 4.65: Drying Rate Constant against drying Temp at 0.6 m/s Air Velocity

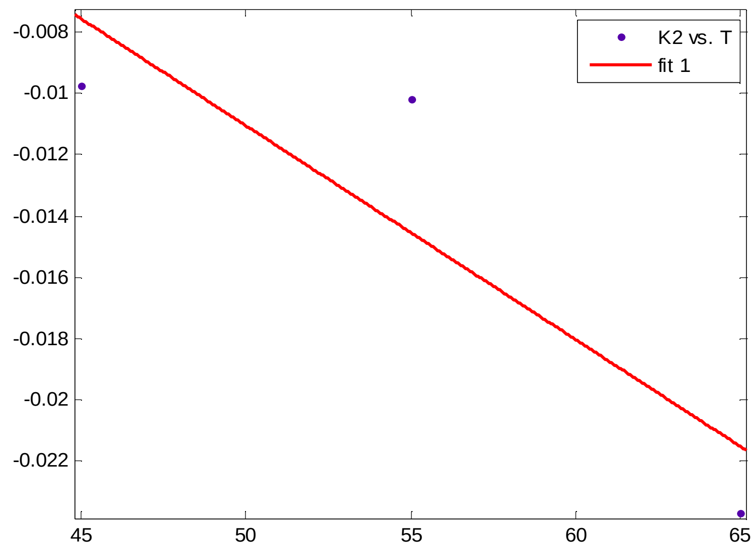


Fig 4.66: Drying Rate Constant against drying Temp at 1.0 m/s Air Velocity

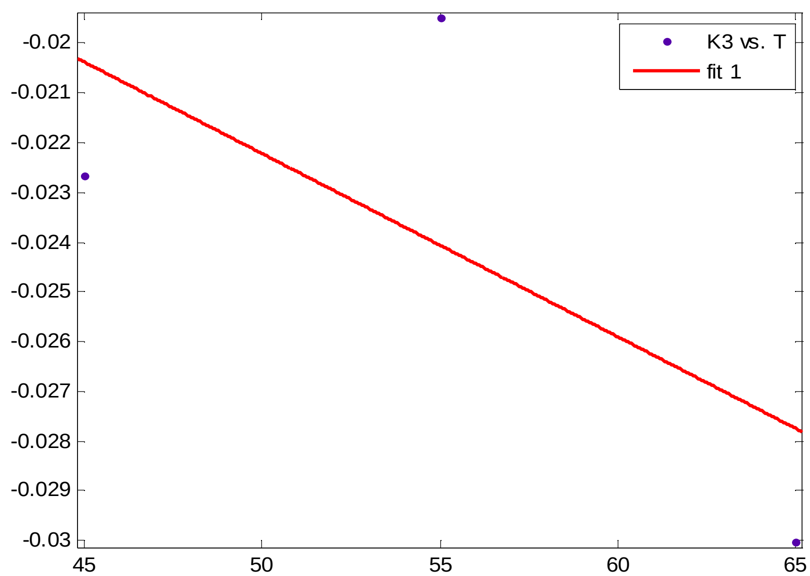


Fig 4.67: Drying Rate Constant against drying Temp at 1.5 m/s Air Velocity

4.1.5 MOSITURE DIFFUSIVITY AND ACTIVATION ENERGY OF MOISTURE DIFFUSION

Table 4.8: Values of Drying Rate constants (k), Moisture Diffusivity (D_{eff}) and Activation Energy (Ea) at various Drying Temperatures and Air Velocity

	Air Velocity (m/s)					
	0.6		1.0		1.5	
Temp. (^{0}C)	k	Deff (m^2/s)	k	Deff (m^2/s)	k	Deff (m^2/s)
45	-0,0152	2,09E-09	-0,00972	1,33037E-09	-0,02268	3,10421E-09
55	-0,0177	2,42396E-09	-0,01016	1,3906E-09	-0,01948	2,66622E-09
65	-0,02	2,73739E-09	-0,02371	3,24518E-09	-0,03003	4,1102E-09
Ea(kJ/mol)	26,29078223		30,57012178		26,35264679	

4.2 DISUSSIONS

4.2.1 PHYSICAL CHARACTERISTICS OF GROUNDNUT SEEDS

The physical properties of groundnut seeds L_1, L_2, and L_3 were measured at a moisture content of 67(db) and the following results were obtained: 17.299 ± 0.806mm, 9.422± 0.621mm and 7.396± 0.815mmrespectively.

The calculated physical properties were shown in table 4.1.

4.2.2 DRYING CHARACTERISTICS OF GROUNDNUTS

During the drying, the rate of moisture release to the drying air tends to reduce with time. This was evident in the shape of the drying curves when the moisture content was plotted against the drying duration as shown in figure 4.1 to 4.3 there was a steep slope at the beginning which characterized constant rate period. This period gave way to a gentler slope and decreasing rate of moisture reduction till the equilibrium moisture content was attained. Generally, from the graph, the constant rate period ended 30 to 50 minutes after the beginning of drying and varies with differences in drying temperatures.

4.2.2.1. DRYING CURVES

Groundnuts at average initial moisture content of 67% (d.b.) were dried to average final moisture content when there is little or no change in weight. The final moisture contents represent moisture equilibrium between the samples and drying air under dryer conditions, beyond which any changes in the mass of sample with time were insignificant. The graphs of the moisture content (d.b.) were plotted against the drying time for all the drying temperatures and air velocities as shown in figures 4.1 to 4.3. This corresponds with Goyal et al (2014) for potato mash and Hii, et al (2009) for cocoa.

4.2.2.2. DRYING RATE (D_r) CURVES

Drying rate of the groundnut seeds was calculated using the following

$$tD_r = \frac{M_{t+dt} - M_t}{dt} \quad (4.1)$$

(Akpinar et al., 2003). Where, M_t and $M_{t+dt}$are the moisture content at *t* and moisture ratio at *t+dt*, respectively; t is drying time (min).

Figure 4.4 to 4.6 shows the plot of drying rate against time. The drying rate was obtained by calculating the time to remove a given quantity of moisture from the seeds. The drying rate decreased with an increase in the drying time and increased with temperature.

4.2.2.3. DRYING RATE CONSTANTS (K)

Drying rate constant determined from five thin layer models for groundnut drying data were presented in tables 4.2 to 4.7. These include the Newton model, Page model, Henderson and Pabis model, Logarithmic model and two-term-exponential model obtained from the solution of diffusion equation (approximation of Fick's diffusion model).

Fick's second equation of diffusion was used to calculate effective moisture diffusivity of groundnut seeds, considering a constant moisture diffusivity, infinite cylindrical geometry and uniform initial moisture distribution as shown in Eqn 4.2

$$MR = \frac{M-M_e}{M_o-M_e} = \frac{4}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{eff}t}{4l^2}\right) \qquad (4.2)$$

Where:

$\frac{4}{\pi^2}$ = the shape factor and depends on the geometry of the drying material ($\frac{8}{\pi^2}$for a slab and $\frac{6}{\pi^2}$for the sphere).

D_{eff} = the effective diffusivity, (m^2s^{-1})

L = characteristic length, thickness (m)

n = positive integer

For long drying times, the equations (4.2) can be simplified as equation (4.3) by taking the first term of the series solution and expressed in a logarithmic form as follows (Doymaz, 2012):

$$\boldsymbol{InMR = In\frac{4}{\pi^2} - \frac{\pi^2 D_{eff} t}{4l^2}} \quad (4.3)$$

The effective moisture diffusivity was obtained by plotting the experimental data in terms of ln(MR) versus drying time (mins). From equation (4.2), a plot of ln(MR) versus time gives a straight line with a slope of (k) in which:

$$\boldsymbol{k = \frac{\pi^2 D_{eff} t}{4l^2}} \quad (4.4)$$

The drying curves were transformed to linear forms by taking the logarithm of the moisture ratio against the drying time to get a straight line whose slope is the drying rate constant (k) for the product at the prevailing conditions. The plots of natural log of MR (lnMR), against time (t) at different air velocities are presented in figures 4.10 to 4.18.

The scatter diagrams (figures 4.10 to 4.18) show that the observations are clustered along the linear regression line which means the adequacy of this experiment in describing the drying characteristics of groundnut seeds. Similar findings were reported by Goyal et al. (2006) for raw mango slices, Doymaz and Ismail (2011) for sweet cherry, Aghbashlo et al. (2009) for potato slices and Doymaz (2012) for persimmon slices.

The chart of drying temperatures against drying duration (time) is presented in figure 4.19. Keeping other factors, such as relative humidity and air flow rate, constant it can be seen from figure 4.19 that drying duration varies with temperature of the drying air.

4.2.3 MATHEMATICAL MODELLING OF DRYING CURVES

The drying data obtained (moisture ratio against drying time) for the three temperature samples and varying air velocities, were fitted into the five thin layer models (table 3.2). The curve fittings are presented from figure 4.20 to 4.64, while the model parameters are presented in tables 4.2, 4.3 and 4.4.

It can be deduced from table 4.2 - 4.4 that increase in air velocity increases shrinkage as it is evident that ‘A’ shape factor increases with an increase in air velocity across all the temperatures.

The models were evaluated based on coefficient of determination (R^2), Sum of Square Errors (SSE) and Root Mean Square Error (RMSE). The higher values for R^2 and lower values for SSE and RMSE are chosen as the criteria for goodness of fit (Mirzaee et al., 2009). The evaluations are presented in tables 4.5, 4.6 and 4.7. The R^2 values varied between 0.9621 and 0.9978, except for the Newton model that gave high error with negative R^2. These values show that four out of the five tested drying models predict thin layer drying process of groundnut adequately.

From Table 4.5, it can be concluded that the best model for air velocity of 0.6m/s is the Page Model, since it has the highest R^2 and least errors. And it gave the best fit at 45^0C.

Similarly, from Table 4.7, it can be concluded that the best model for air velocity of 1.0 m/s is the Two-term model, at 45^0C.

From Table 4.8, it can also be concluded again, that the best model for air velocity of 1.5 m/s is the Page model at 65^0C.

In general, it is the Page model at 45^0C drying air temperature and air velocity of 0.6 m/s that gave the best fit.

4.2.4 EFFECT OF TEMPERATURE ON THE DRYING RATE CONSTANT

From the analysis presented in tables 4.65 to 4.67 it is not difficult to see that the drying rate constant increases with increase in temperature in the range of the temperatures tested. The plot of the drying rate constant (k) against temperature for air velocities of 0.6, 1.0 and 1.5 m/s are presented in figure 4.65, 4.66 and 4.67 respectively.

4.2.5 MOSITURE DIFFUSIVITY AND ACTIVATION ENERGY OF MOISTURE DIFFUSION

The values of effective moisture diffusivity obtained from this study lie within the general range from 10^{-11} to 10^{-9} m^2/s for food materials (Madamba *et al.,* 1996). The determined values of the effective moisture diffusivity (D_{eff}) for the different temperatures are shown in table 4.9. The diffusivity values were found to be 3.35 x $10^{-11}$to 9.21 10^{-11} m^2/s at 45 to 65ºC. It is clear that effective diffusivity values for groundnut seeds increases greatly with increasing drying air temperature, which agrees with Akpinar *et al.,* (2003) and Thorat *et al.,* (2010).

The minimum value of the moisture diffusivity was determined at the air velocity of 1.0 m/s and air temperature of 45°C while the maximum value was at the air velocity of 1.5m/s and air temperature of 65°C. Generally, the value of D_{eff} falls in the range reported for food materials (Aghbashlo*et al*., 2008). The values of the effective moisture diffusivity (Deff) are consistent with the reported; the lowest effective moisture diffusivity was 1.33x 10^{-9} m^2/s at air velocity of 1.0 m/s at temperature of 45^{o}C. The highest effective diffusivity was to 4.11x 10^{-9} m^2/s at air velocity of 1.5 m/s at temperature of 65^{o}C.

The activation energy can be interpreted as the minimum energy required to break solid-water or water-water interactions and to move water molecules from inside to the surface of a solid. A smaller Ea value of a sample indicates that water molecules can move more readily in the solid (Darvishi, 2012). The activation energy (Ea) was found to be 26.29 kJ/molto 30.57 kJ/mol. The activation energy value obtained from this study lies within the general range of 12.7 to 110 kJ/mol for various food materials (Zogzas *et al.*, 1996).

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 SUMMARY

A research of the drying kinetics of groundnut seeds was carried out with a convective crop dryer, to generate design data for the seeds and similar crops drying systems. Thin-layer model parameters used in this study were experimentally determined, using curve fitting methods. This led to suitable selection of appropriate drying models for groundnut seeds which were used in this study. Excel and Matlab toolbox programs were extensively used in the analysis of the data. It was observed that the effect of the air temperature on total drying rate is more important than any other parameter such as air velocity and relative humidity, in thin-layer drying of groundnut seeds as observed from graphs. The drying process was observed to occur in the falling rate period for all the drying experiments carried out, which is a widely reported phenomenon for agricultural materials

5.2 CONCLUSIONS

Five thin layer drying models were investigated using the experimental data describing the drying behaviour of groundnut seeds. Comparisons of the drying rate models showed high coefficient of determination for Page model, two-term model, followed by Logarithmic, Henderson and Pabis model, and then the

Newton Modelof which hashigh error and low coefficient of determination. Any one of these five models can be used to simulate the drying behaviour of groundnut seeds.

It was observed that the drying rate was a decreasing function of time. However, there was a short constant rate period. This was indicated in the graphs of drying rate against time in figure (4.2). Consequently, the drying rate is an inverse function of time of drying.

The statistical error analysis showed goodness of fit which was good enough to guarantee validity in predicting the drying parameters.

The drying coefficient (rate constant) was observed to have an inverse relationship with time and increase in temperature.

The lowest effective moisture diffusivity was 1.332x 10^{-9} m^2/s at air velocity of 1.0 m/s at temperature of 45^oC. The highest effective diffusivity was to 4.11x 10^{-9} m^2/s at air velocity of 1.5 m/s at temperature of 65^oC.

The trend in the behaviour of moisture diffusivity can be explained with the fact that at low velocity (1.0 m/s), the air has a better contact with the sample surface which resulted in a greater absorption of moisture, consequently the moisture gradient of the sample with the drying air increases and leads to an increase in the moisture diffusivity. At higher velocity (1.5m/s), the air passes through the sample in turbulent and faster rate, thereby decreasing the moisture gradient. This leads to reduction in the moisture diffusivity.

The activation energy of groundnut seeds drying was found to be in the range of 26.29 kJ/mol - 30.57 kJ/mol. The activation energy value obtained from this study lies within the general range of 12.7 to 110 kJ/mol for various food materials (Zogzas *et al*., 1996).

5.3. CONTRIBUTION TO KNOWLEDGE

i. Suitable models were evaluated for simulation of drying characteristics of groundnuts.

ii. Among the models; Page was found to accurately simulate the drying behaviour of groundnut seeds.

iii. Almost all the parameters characterizing the drying of groundnut seeds were influenced by temperature, Relative humidity and air velocity.

iv.The effective moisture diffusivity of groundnut seeds ranges from 1.33x 10^{-9} m^2/s to 4.11x 10^{-9} m^2/s in the range of air velocity of 0.6 m/s to 1.5m/s and temperature of 45^oC to 65^0C.

v. The activation energy of groundnutseeds drying was found to be in the range of 26.29 kJ/mol to 30.57 kJ/mol for the same range of air velocity of 0.6 m/s to 1.5m/s and temperature of 45^0C to 65^0C.

It will be observed that these information, though very important in design and analysis of drying and storage systems, are acutely lacking in the literature for most Nigerian crops. This dearth of information has created gap in the design process of drying systems for these affected local agricultural products. The results of this research are part of the humble efforts in breaching this gap in knowledge.

5.4. RECOMMENDATIONS

This work was conceived as a foundation work for development of a dryer for applications. It is recommended that the determined parameters should be directly applied in estimating energy needs of drying crops.

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APPENDICES

A: SUMMARY OF THE EXPERIMENTAL RESULTS AND SUMMARY OF DESIGN AND AIR PARAMETERS

Table A.1: Experimental data at Temperature of 45°Cand Air velocity of 0.6 m/s

Av. Temp. (°C)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
45	44.125	0.6	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1	0.000000	0.042866913
15	0.961710275	-0.039042	0.041225551
30	0.843012125	-0.170774	0.036137327
45	0.746649649	-0.292159	0.032006565
60	0.6464582	-0.436247	0.027711667
75	0.56413529	-0.572461	0.024182738
90	0.48181238	-0.730200	0.020653809
105	0.410976388	-0.889220	0.017617289
120	0.340778558	-1.076522	0.014608125
135	0.275686024	-1.288493	0.011817809
150	0.21952776	-1.516277	0.009410477
165	0.167198468	-1.788574	0.007167282
180	0.135290364	-2.000332	0.00579948
195	0.104658583	-2.257052	0.00448639
210	0.078493937	-2.544734	0.003364793
225	0.057434588	-2.857109	0.002462043
240	0.03956605	-3.229784	0.001696074
255	0.023611997	-3.746000	0.001012173
270	0.011486918		0.000492409
285	0		0

Table A.2: Experimental data at temperature of 45°Cand Air velocity of 1.0 m/s

Av. Temp. (^oC)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
45	44.125	1.0	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1.000649772	0.000650	0.041615998
15	0.912930474	-0.091096	0.037967842
30	0.77322937	-0.257180	0.032157817
45	0.649122807	-0.432133	0.026996352
60	0.532163743	-0.630804	0.022132144
75	0.430149448	-0.843623	0.017889474
90	0.352826511	-1.041779	0.014673693
105	0.300194932	-1.203323	0.012484799
120	0.254061079	-1.370181	0.01056614
135	0.215724496	-1.533753	0.008971761
150	0.191033138	-1.655308	0.007944872
165	0.171539961	-1.762939	0.007134171
180	0.155295647	-1.862425	0.006458587
195	0.141650422	-1.954393	0.005891096
210	0.115659519	-2.157105	0.004810161
225	0.10331384	-2.269984	0.004296717
240	0.104613385	-2.257484	0.004350763
255	0.09811566	-2.321608	0.00408053

Table A3: Experimental data at temperature of 45^{o}C and Air velocity of 1.5 m/s

Av. Temp. (^{o}C)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
45	44.125	1.5	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	0.99740091	-0.002602	0.041480881
15	0.89928525	-0.106155	0.037400351
30	0.786874594	-0.239686	0.032725307
45	0.640025991	-0.446246	0.026618025
60	0.509421702	-0.674479	0.021186326
75	0.386614685	-0.950327	0.016078908
90	0.303443795	-1.192559	0.012619916
105	0.237816764	-1.436255	0.009890555
120	0.178037687	-1.725760	0.007404405
135	0.132553606	-2.020768	0.005512769
150	0.098765432	-2.315008	0.004107553
165	0.072124756	-2.629358	0.002999595
180	0.046133853	-3.076208	0.00191866
195	0.027290448	-3.601219	0.001134982
210	0.014294997	-4.247846	0.000594514
225	0.001949318	-6.240276	8.10701E-05

Table A4: Experimental data at temperature of 55^{o}C and Air velocity of 0.6 m/s

Av. Temp. (^{o}C)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
55	19.58	0.6	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1	0.000000	0.041588974
15	0.920727745	-0.082591	0.038292123
30	0.796621183	-0.227376	0.033130658
45	0.686159844	-0.376645	0.028536684
60	0.586094867	-0.534274	0.024375084
75	0.500974659	-0.691200	0.020835022
90	0.415204678	-0.878984	0.017267937
105	0.341780377	-1.073587	0.014214295
120	0.276153346	-1.286799	0.011484934
135	0.213775179	-1.542830	0.00889069
150	0.166991553	-1.789812	0.006945007
165	0.121507472	-2.107780	0.005053371
180	0.088369071	-2.426233	0.003675179
195	0.063677713	-2.753921	0.002648291
210	0.044834308	-3.104782	0.001864613
225	0.03118908	-3.467687	0.001297122

	4		

Table A.5: Experimental data at temperature of 55^oC and Air velocity of 1.0 m/s

Av. Temp. (^oC)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
55	19.58	1.0	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1.000000001	6.19139E-10	0.04233279
15	0.905587669	-0.099171188	0.038336052
30	0.754656391	-0.281492745	0.03194671
45	0.621066153	-0.476317676	0.026291463
60	0.504816956	-0.683559379	0.02137031
75	0.396274888	-0.925647147	0.016775421
90	0.317919075	-1.145958409	0.013458401
105	0.263326911	-1.334359012	0.011147363
120	0.215157354	-1.536385639	0.009108211
135	0.195889531	-1.630204395	0.00829255

150	0.177263969	-1.730115305	0.007504078
165	0.163134233	-1.813181904	0.006905927
180	0.149646757	-1.899477718	0.006334965
195	0.136801542	-1.989224006	0.005791191
210	0.124598587	-2.082658012	0.005274606
225	0.113037893	-2.180032176	0.004785209
240	0.102761721		

Table A.6: Experimental data at temperature of 55^{o}Cand Air velocity of 1.5 m/s

Av. Temp. (^{o}C)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
55	19.58	1.0	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1	1.26414E-10	0.04011209
15	0.892215569	-0.114047506	0.035788631
30	0.704590818	-0.350138044	0.02826261
45	0.550232868	-0.597413695	0.02207099
60	0.417831005	-0.872678223	0.016760075
75	0.30405855	-1.190534999	0.012196424
90	0.212907518	-1.546897394	0.008540165
105	0.153692615	-1.872800679	0.006164932
120	0.100465735	-2.297938553	0.004029891
135	0.079840319	-2.527726647	0.003202562
150	0.05988024	-2.815408719	0.002401922
165	0.045908184	-3.081111885	0.001841473
180	0.032601464	-3.423398092	0.001307713
195	0.027278776	-3.601646323	0.001094209
210	0.02328676	-3.759870328	0.000934081

Table A.7: Experimental data at temperature of 65°Cand Air velocity of 0.6 m/s

Av. Temp. (°C)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
65	26.68	0.6	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1,0000000	0	0.042302981
15	0,8073197	-0.115132112	0.037702464
30	0,5780409	-0.289829378	0.031659181
45	0,4198062	-0.43187251	0.027466993
60	0,2852530	-0.592818609	0.023383694
75	0,2346609	-0.780509619	0.019382061
90	0,1883746	-0.997701814	0.015598203
105	0,1646932	-1.250513249	0.012113788
120	0,1334769	-1.534456999	0.009119368
135	0,1141012	-1.88052739	0.006451613
150	0,0914962	-2.285992498	0.004301075
165	0,0688913	-2.743417345	0.0027222
180	0,0452099	-3.271050087	0.001606098
195	0,0247578	-3.659708077	0.00108888
210	0,0118407	-4.404148552	0.000517218
225	0,0010764		0

Table A.8: Experimental data at temperature of 65^{o}Cand Air velocity of 1.0 m/s

Av. Temp. (^{o}C)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
65	26.68	1.0	0.00535
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1	0	0.040031962
15	0.870924817	-0.138199624	0.034864829
30	0.677312043	-0.389623193	0.02711413
45	0.550232868	-0.597413695	0.022026901
60	0.435795077	-0.830583154	0.017445732
75	0.325349301	-1.1228559	0.013024371
90	0.230206254	-1.468779615	0.009215608
105	0.162341983	-1.818050164	0.006498868
120	0.113772455	-2.173554833	0.004554535
135	0.081170991	-2.511197345	0.003249434
150	0.051896208	-2.958509563	0.002077507
165	0.03992016	-3.220873828	0.001598082
180	0.02661344	-3.626338936	0.001065388
195	0.012641384	-4.370779411	0.000506059
210	0.004594666	-	0.000160192

		5.382859296	

Table A.9: Experimental data at temperature of 65°C and Air velocity of 1.5 m/s

Av. Temp. (°C)	**Relative Humidity (%)**	**Air Velocity (m/s)**	**Av. Seed Thickness (m)**
65	26.68	1.0	0.007396
Drying Time (mins)	**Moisture Ratio**	**Log (MR)**	**Drying Rate (%MC/min)**
0	1	0	0.040251
15	0.854014599	-0.157806991	0.034375
30	0.648971466	-0.432366529	0.026122
45	0.504313205	-0.684557765	0.020299
60	0.403450564	-0.907701317	0.016239
75	0.282680823	-1.263436852	0.011378
90	0.180491042	-1.712074132	0.007265
105	0.110816191	-2.199882386	0.004460
120	0.050431321	-2.987142858	0.002030
135	0.02986065	-3.511213709	0.001202
150	0.01725282	-4.059779661	0.000694
165	0.00597213	-5.120651621	0.000240
180	0		

Table A.10: Data for temperature of 45^{o}C and Air velocity of 0.6m/s

Summary of Drying Conditions		
Average. Temperature. (^{o}C)	**Initial Moisture Content (%db)**	**Relative Humidity (%)**
45	67	44.125

Drying Experiment	
Drying Time (mins)	**Moisture Content (db)**
0	0.643003693
15	0.618383258
30	0.54205991
45	0.480098482
60	0.41567501
75	0.362741075
90	0.30980714
105	0.264259335
120	0.219121871
135	0.177267132
150	0.14115716
165	0.107509233
180	0.086992204
195	0.067295856
210	0.050471892
225	0.036930652
240	0.025441116
255	0.015182602
270	0.00738613
285	0

Table A.11: Data for temperature of 45^{o}C and Air velocity of 1.0m/s

Summary of Drying Conditions		
Average. Temperature. (^{o}C)	**Initial Moisture Content (%db)**	**Relative Humidity (%)**
45	67	44.125

Drying Experiment	
Drying Time (mins)	**Moisture Content (db)**
0	0.624239968
15	0.569517633
30	0.482367248
45	0.404945278
60	0.331982165
75	0.268342116
90	0.220105391
105	0.18727199
120	0.158492096
135	0.134576409
150	0.119173085
165	0.107012566
180	0.0968788
195	0.088366437
210	0.072152412
225	0.06445075
240	0.065261451
255	0.061207945

Table A.12: Data for temperature of 45^{o}C and Air velocity of 1.5 m/s

Summary of Drying Conditions		
Average. Temperature. (^{o}C)	**Initial Moisture Content (%wb)**	**Relative Humidity (%)**
45	67	44.125
Drying Experiment		
Drying Time (mins)	**Moisture Content (db)**	
0	0.622213214	
15	0.56100527	
30	0.490879611	
45	0.399270369	
60	0.317794893	
75	0.241183624	
90	0.189298743	
105	0.14835833	
120	0.111066072	
135	0.082691528	
150	0.061613296	
165	0.04499392	
180	0.028779895	
195	0.017024726	
210	0.008917714	
225	0.001216052	

Table A.13: Data for temperature of 55^{o}C and Air velocity of 0.6m/s

Summary of Drying Conditions		
Average. Temperature. (^{o}C)	**Initial Moisture Content (%db)**	**Relative Humidity (%)**
55	67	19.58

Drying Experiment	
Drying Time (mins)	**Moisture Content (db)**
0	0.623834617
15	0.57438184
30	0.49695987
45	0.428050263
60	0.365626267
75	0.312525334
90	0.259019051
105	0.21321443
120	0.172274017
135	0.133360357
150	0.104175111
165	0.075800567
180	0.055127685
195	0.039724362
210	0.027969193
225	0.01945683

Table A.14: Data for temperature of 55^{o}C and Air velocity of 1.0m/s

Summary of Drying Conditions		
Average. Temperature. (°C)	**Initial Moisture Content (%db)**	**Relative Humidity (%)**
55	67	19.58

Drying Experiment	
Drying Time (mins)	**Moisture Content (wb)**
0	0.634991843
15	0.575040783
30	0.479200653
45	0.394371941
60	0.320554649
75	0.251631321
90	0.20187602
105	0.16721044
120	0.136623165
135	0.124388254
150	0.112561175
165	0.103588907
180	0.09502447
195	0.086867863
210	0.079119086
225	0.07177814
240	0.065252855

Table A.15: Data for temperature of 55°C and air velocity of 1.5m/s

Summary of Drying Conditions		
Average. Temperature. (°C)	**Initial Moisture Content (%db)**	**Relative Humidity (%)**
55	67	19.58

Drying Experiment	
Drying Time (mins)	**Moisture Content (db)**
0	0.601681345
15	0.536829464
30	0.423939151
45	0.331064852
60	0.251401121
75	0.182946357
90	0.128102482
105	0.092473979
120	0.060448359
135	0.048038431
150	0.036028823
165	0.027622098
180	0.019615693
195	0.016413131
210	0.014011209

Table A.16: Data for temperature of 65^{o}C and Air velocity of 0.6m/s

Summary of Drying Conditions		
Average. Temperature. (^{o}C)	**Initial Moisture Content (%db)**	**Relative Humidity (%)**
65	67	26.68

Drying Experiment	
Drying Time (mins)	**Moisture Content (db)**
0	0.634544712
15	0.565536954
30	0.474887709
45	0.4120049
60	0.35075541
75	0.290730911
90	0.23397305
105	0.181706819
120	0.136790527
135	0.096774194
150	0.064516129
165	0.040832993
180	0.024091466
195	0.016333197
210	0.007758269
225	0

Table A.17: Data for temperature of 65^oC and Air velocity of 1.0m/s

Summary of Drying Conditions		
Average. Temperature. (^oC)	**Initial Moisture Content (%wb)**	**Relative Humidity (%)**
65	67	26.68
Drying Experiment		
Drying Time (mins)	**Moisture Content (wb)**	
0	0.600479425	
15	0.522972433	
30	0.406711946	
45	0.330403516	
60	0.261685977	
75	0.195365561	
90	0.138234119	
105	0.09748302	
120	0.068318018	
135	0.04874151	
150	0.031162605	
165	0.023971235	
180	0.015980823	
195	0.007590891	
210	0.002402883	

Table A.18: Data for temperature of 65^{o}C and Air velocity of 1.5 m/s

Summary of Drying Conditions		
Average. Temperature. (^{o}C)	**Initial Moisture Content (%wb)**	**Relative Humidity (%)**
65	29	26.68

Drying Experiment	
Drying Time (mins)	**Moisture Content (wb)**
0	0.603766026
15	0.515625
30	0.391826923
45	0.304487179
60	0.243589744
75	0.170673077
90	0.108974359
105	0.066907051
120	0.030448718
135	0.018028846
150	0.010416667
165	0.003605769
180	0

Table A. 19: Physical properties of the air at the average drying chamber temperature

Parameter	Dry bulb temperature, (Ts ,°C)°C		
	45	55	65
T_{wb-s} (°C)	24.5	27.2	29.6
T_{av-s} (°C)	39.8	46	52.3
ρ_a (kg/m^3)	1.13	1.11	1.09
μ_a(kg/m.s)	0.00 0019	0.000019	0.000019
C_{p-a} (J/kg.K)	1006 .06	1006.42	1006.81
N_{Re}	152. 94	147.69	142.66
N_{Sc}	0.56	0.56	0.55
N_{Sh}	6.77	6.63	6.50
K_{air} (m/s)	0.00 3	0.0031	0.0031

Table A.20: Major Drying Air Parameters at Temperature of 45°C

s/n	**Drying Air Condition**	**Ambient Air**	**Drying Chamber Air**	**Exhaust Air**
1	Dry Bulb Temperature (°C)	32	45.2	41
2	Wet Bulb Temperature (°C)	29	33.3	36.30
3	Relative Humidity (%)	94	44.125	73.612
4	Mixing Ratio (g/kg)	29	27.183	37.39
5	Specific Volume (m^3/kg)	0.8793	0.9158	0.9095
6	Enthalpy (kJ/kg)	106.43	196.97	137.58
7	Dew point Temperature (°C)	31.022	29.939	35.328

8	Density (kg/m^3)	1.1373	1.092	1.0996
9	Sat. Vapor Pressure (mbar)	47.717	96.162	78.058
10	Absolute Humidity (g/m^3)	32.053	29.939	39.632

Table A.21: Major Drying Air Parameters at Temperature of 55^{o}C

s/n	Drying Air Condition	Ambient Air	Drying Chamber Air	Exhaust Air
1	Dry Bulb Temperature (^{0}C)	33.6	55.8	51.6
2	Wet Bulb Temperature (^{0}C)	29.2	32.6	49.6
3	Relative Humidity (%)	72.26	19.58	89.594
4	Mixing Ratio (g/kg)	24.04	20.119	83.551
5	Specific Volume (m^3/kg)	0.8814	0.9431	0.9631
6	Enthalpy (kJ/kg)	95.419	108.52	268.8

7	Dew point Temperature (^oC)	27.901	24.982	49.377
8	Density (kg/m^3)	1.1346	1.0604	1.0383
9	Sat. Vapor Pressure (mbar)	52.205	164.07	133.94
10	Absolute Humidity (g/m^3)	26.639	20.914	80.066

Table A.22: Major Drying Air Parameters at Temperature of 65^oC

s/n	Drying Air Condition	Ambient Air	Drying Chamber Air	Exhaust Air
1	Dry Bulb Temperature (^0C)	32.9	65.8	61.9
2	Wet Bulb Temperature (^0C)	28.8	42.6	59.7
3	Relative Humidity (%)	79.92	26.68	89.70
4	Humidity Ratio (g/kg)	24.202	45.694	148.77
5	Specific Volume (m^3/kg)	0.8766	0.9857	1.0239

6	Enthalpy (kJ/kg)	94.4	186.01	451.29
7	Dew point Temperature (^oC)	28.01	38.782	59.54
8	Density (kg/m^3)	1.1408	1.1346	0.9767
9	Sat. Vapor Pressure (mbar)	47.447	259.93	218.05
10	Absolute Humidity (g/m^3)	26.958	44.332	126.49

Table A 23: Input properties of Groundnut, water and air for the models

s/n	Property Name	Value of property	Property Unit
1	Density of Groundnut (ρ_t)	987	kg/m^3
2	Moisture Content (dry basis)	0.67	kg/kg
3	Latent Heat of Evaporation, (h_{fg})	2358600	J/kg
4	Thermal Conductivity of air, (K_a)	0.0287	w/Mk
5	Density of water,(ρ_w)	994.59	kg/m^3
6	Dynamic viscosity of air, (μ_a)	1.839×10^{-5}	N-S/m^2
7	Specific Heat of air, (Cp_a)	1005.04	J/kgK
8	Density of air, (ρ_{air})	1.173	kg/m^3
9	Equilibrium moisture content,	0.29	kg/kg

	(M_e)		
10	Specific Heat of water, ($C_{p,a}$)	4184	J/kg
11	Kinematic viscosity of air(v_a)	1.552×10^{-5}	m^2/s
12	Universal gas constant (R_u)	8.314	m^2/kmol.K

Table A24 : MEASURED PHYSICAL PROPERTIES OF GROUNDNUT

S/NO	Major Diameter	Intermediate Diameter	Minor Diameter	Weight
1	18,45	9,32	8,45	0,628
2	16,1	7,64	7,1	0,596
3	18,12	9,02	8,75	0,619
4	17,5	8,13	6,37	0,598
5	18,32	9,33	7,4	0,627

6	17,41	7,61	6,3	0,575
7	16,2	8,29	8,27	0,589
8	18,11	7,37	6,2	0,595
9	16,25	8,3	8,11	0,59
10	17,36	9,4	7,39	0,597
11	15,51	8,41	6,41	0,55
12	16,32	7,52	7,44	0,588
13	18,45	9,5	8,35	0,631
14	17,37	7,6	6,6	0,581
15	18,5	9,1	7,59	0,626
16	17,12	8,51	8,32	0,611
17	16,47	7,63	6,47	0,607
18	17,54	8,8	7,15	0,622
19	18,49	7,47	8,8	0,598
20	16,37	9,21	6,29	0,609
21	18,27	8,45	7,48	0,624
22	17,19	9,8	8,15	0,62
23	16,33	7,33	6,23	0,586
24	18,2	9,71	7,68	0,622
25	16,41	7,59	8,73	0,584
26	17,21	8,81	6,24	0,599
27	16,17	9,3	8,35	0,61
28	18,43	7,12	7,58	0,593
29	17,17	9,03	6,95	0,62
30	18,22	8,22	7,54	0,61
31	17,29	7,97	6,78	0,597
32	15,11	9,1	8,17	0,559

33	17,31	8,59	6,25	0,598
34	18,57	7,77	7,72	0,625
35	16,3	9,2	8,34	0,615
36	18,53	8,67	7,65	0,623
37	17,4	7,39	6,76	0,595
38	16,54	9,76	8,19	0,599
39	17,23	7,07	7,93	0,601
40	16,55	9,29	8,33	0,6
41	18,13	8,15	7,49	0,62
42	17,59	7,83	6,98	0,615
43	18,39	9,14	5,61	0,626
44	16,6	8,57	7,53	0,593
45	18,19	9,11	6,38	0,625
46	17,44	7,93	8,85	0,596
47	16,21	9,7	5,43	0,589
48	18,14	8,1	8,9	0,621
49	17,38	7,9	7,28	0,595
50	16,5	9,42	6,55	0,588