**A**

**THESIS**

**ON**

# Prediction of Drying Kinetics of Different Vegetables in a Fluidized Bed Drier

In partial fulfillment of the requirements of

Bachelor of Technology (Chemical Engineering)

SUBMITTED BY

**Sayed Mohammed Atif**

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Under the Guidance of

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**NATIONAL INSTITUTE OF TECHNOLOGY**

**ROURKELA**

**National Institute of Technology**

**Rourkela**

## CERTIFICATE

This is to certify that this thesis entitled, "PREDICTION OF DRYING KINETICS OF DIFFERENT VEGETABLES IN A FLUIDIZED BED DRIER" submitted by Mr. Sayed Mohammed Atif in partial fulfillments for the requirements for the award of Bachelor of Technology Degree in Chemical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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Abstract

*A study has been conducted on the kinetics of drying of vegetables in a fluidized bed drier. The experiments had been conducted on vegetables in a fluidized bed drier with a conical bed. Various parameters like time of drying, temperature of air, flow velocity of air and material to be dried were varied and the drying rates were determined. The drying rates were then compared to two thin layer drying models 'Page' and 'Wang and Singh). The coefficient of determination ($R^2$) and root mean square error (RMSE) were evaluated. The models can appropriately describe the drying kinetics of vegetables considering the different experimental conditions. The effective diffusivity was determined using the Fick's model. A correlation was developed between the moisture ratio and the parameters. The values obtained from the correlation were compared to the experimental values which gave deviation within experimental limits. Finally the effect of each parameter on the drying rate was determined*

***KEYWORDS:*** *temperature, drying, diffusivity, Fick's second law*

## CONTENTS

## NOMENCLATURE

| | | |
|---|---|---|
| t | : | Drying time, second |
| $U_o$ | : | Velocity of the fluidizing medium, m/s. |
| $\Delta t$ | : | Drying time interval, |
| $U_{max}$ | : | Maximum fluidization velocity, m/s |
| $\theta$ | : | Temperature , $^{\circ}$C |
| $R^2$ | : | Coefficient of determination |
| RMSE | : | Root mean square error |
| k | : | Drying rate constant |
| n | : | Model constant |
| Mt | : | Moisture content at anytime (kg water/kg dry solid) |
| Mo | : | Initial moisture content (kg water/kg dry solid) |
| Me | : | Equilibrium moisture content of samples (kg water/kg dry solid) |

## Abbreviations

| | | |
|---|---|---|
| MR | : | Moisture ratio |
| Cal | : | Calculated |
| Exp | : | Experimental |

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# Chapter 1

# INTRODUCTION

Drying is a method of preserving food by reducing water activity, thus preserving foods by avoiding microbial growth and deteriorative chemical reactions. The Drying Process leads to reduction of the moisture content in solids, to maintain their consistency in storage and transport. The main purposes of drying are to increase shelf life, reduce packaging and storage costs, lower transporting weights, improve sensory qualities, store flavors, and preserve nutritional value. For storage purposes, the moisture content of materials must fall within a suitable range so that they do not undergo any type of deterioration or alterations in quality or characteristics. To achieve the desired moisture content, the material must be dried.

Drying is a process of simultaneous heat and mass transfer. Heat required for evaporation, is supplied to the particles of the material and moisture vapor is removed from the material into the drying medium. Heat is transported by convection from the surroundings to the particle surfaces, and from there, by conduction, further into the particle. Moisture is transported in the opposite direction as a liquid or vapor on the surface; it evaporates and passes on by convection to the surroundings. **[Ozbey et. al (2005)]**

The heat needed for drying is supplied to the material by one of the following methods:

- Radiation drying.
- Convective drying (using a drying medium, i.e., air).
- Contact drying (by conduction from a surface that is in direct contact with the material to be dried).

Drying requires high energy input because of the high latent heat of vaporization of water and low energy efficiency of industrial dryers. Lot of energy is wasted in inefficient drying.

Fluidization is the operation by which fine solids are transformed into a fluid like state through contact with a gas or solid. The process of fluidization with hot air is highly attractive for the drying of different materials. Fluidized beds are currently used commercially for drying such materials as granular materials, cereals, polymers, chemicals, pharmaceuticals, fertilizers, crystalline products and minerals.

An induced draught is created by means of blower and fresh air is sucked into the unit. This hot air stream expands the material at certain velocity and creating turbulence in the product. The Fluidization produces full agitation of solid particles by hot air; thereby heat transfer is extremely high and uniform. The product is dried fast without appreciable loss of heat. Filter bags prevent particle escaping from the dryer.

# Chapter 2

# LITERATURE REVIEW

## 2.1 Previous work on fluidized bed drying

Drying refers to the removal of moisture or liquid from a wet solid by transferring this moisture into a gaseous state. In most drying operations, water is the liquid evaporated and air is the drying medium.

When a wet solid is subjected to thermal drying, two processes occur simultaneously:

- Transfer of energy from the surrounding environment to evaporate the surface moisture.
- Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to process 1.

In process 1, the removal of water from the surface as vapor depends on the external conditions of temperature, air humidity and flow, area of exposed surface. In process 2, the movement of moisture internally inside the solid is a function of the physical nature of the solid, its moisture content and the bed temperature. **[Satish S et. al (2005)]**

Recent developments of the regime of fluidization and subsequent design modifications have made fluidized bed drying a desirable choice among other dryers. However, like other types of conventional convective drying processes, fluidized bed drying is a very energy intensive process in industry. The efficiency of a conventional drying system is usually low, depending on the inlet air temperature and other conditions. It is, therefore, desirable to improve the efficiency of the drying process to reduce the overall consumption of energy.

Fluidized drying of granular products of solids can be either batch wise or continuous. Batch operation is preferred for small scale production and for heat sensitive materials. Fluidized bed dryers are widely used in a number of industry sectors to dry finely divided 50–5000 μm particulate materials. Compared with other drying techniques, fluidized bed drying offers many advantages. .**[Ozbey et. al (2005)]**

Many studies have been conducted to determine the parameters that affect drying. The way these parameters affect the drying has also been analysed. The main parameters that have been studied have been temperature of air, velocity of air, material to be dried, size of the particles, time of drying etc. These parameters help us in optimizing the drying process to reduce the cost and drying times. Also, the increasing cost of energy over recent years has prompted and received great attention in order to increase the convective heat transfer rates in the process equipment.

The effect of temperature was more critical than that of the other parameters and could reduce the drying time substantially. **Thomas and Varma (1992)** experimentally investigated fluidized bed drying of granular cellular materials and compared the experimental results for batch and continuous fluidized bed drying investigated at different temperatures and flow rates of the heating medium, particle size and mass of solids in a fluidized bed type dryer. As the product is in close contact with the drying air at low temperature, and also for short duration, the physical and chemical properties of the products are generally not affected and therefore the dryer can effectively be used for heat sensitive products. Due to the continuous movements of product during drying, lump formation, case hardening etc. are minimized.

**Watano et al.(1998)** experimentally studied the drying of wet granules in an agitating fluidized bed type dryer that has a tapered fluidized bed with an agitator blade turning on a central axis installed at the bottom of the cylindrical vessel to impart a tumbling and circulating motion to the granules. The effects of the conditions on the properties of the granules such as the mass median diameter, yield, shape and density of the granules were investigated under various air temperatures, air velocities and agitator rotational speeds. The relationships between the operating conditions and the drying rates were also examined.

**Palancz et. al(1983)** proposed a mathematical model for continuous fluidized bed drying based on the two-phase theory of fluidization. According to this theory, the fluidized bed is divided into two phases, a bubble phase and an emulsion phase, which consists of gas and solid particles

Thus, higher inlet temperatures of drying air can be used which lead to shorter drying times. The enthalpy and the entropy of drying air also increase leading to higher energy efficiency. But increasing inlet air temperature should be limited to obtain good quality dried material. It was experimentally observed by **Hajidavalloo et. al (2000)** that as the inlet air temperature increased the grain temperature also increases. The final temperature of the material after long time spans becomes almost equal to the temperature of inlet drying air.

Drying of biological materials, like fruit and vegetables, in a spouted or spout-fluidized bed is an extremely complicated process due to the simultaneous phenomena of heat, mass and momentum transfer which occurs inside each particle in the bed and transfer phenomena between solid and gas phases of the circulating bed being the mixture of dried granulated material and air. Moreover, the particles of wet material undergo significant shrinkage which affects changes in both the shape and dimensions of the solid. Hot air drying of fruit and vegetables usually provokes changes in physical, chemical, nutritional and biological properties and modifies the characteristics of food products. In most cases these changes are dependent on moisture content, temperature and time of exposition. An understanding of the transfer phenomena taking place during the drying of fruit and vegetables in rotating beds would result in the formulation of adequate mathematical models to optimize the process – leading to improved product quality and a reduction in process costs. Numerous analytical and numerical models have been proposed by various authors to study heat and moisture transfer analysis during drying of different solid objects. Reviews of several different mathematical models have been published. In most cases, the authors employed the finite element method (FEM) for studying temperature and moisture distributions within the wet solids during the drying and control volume (CV) technique to study hydrodynamics and transfer phenomena in fluidized and spouted beds**[Białobrzewski et. al (2008)]**

### 2.2 Advantages of fluidized bed drying

- The even flow of fluidized particles permits continuous, automatically controlled, large- scale operation with easy handling of feed and product.
- There are no mechanical moving parts, that is, it is low maintenance.
- By rapid exchange of heat and mass between gas and particles, overheating of heat sensitive products is avoided.
- Heat transfer rates between fluidized bed and immersed objects, such as heating panels, are high.

- Rapid mixing of solids leads to nearly isothermal conditions throughout the fluidized bed, and thus reliable control of the drying process can be achieved easily.
- It can be operated under lower temperatures.

### 2.3 Disadvantages of some fluidized bed dryers

- In conventional fluidized bed, large column heights are required and formation of channels.
- The principal limitation with the superheated steam drying is the high operating temperature, large equipment like boiler for generating steam, electrical heater for converting saturated steam to super heated steam.
- Agitation fluidized bed dryer consumes high electrical energy for rotation of agitator blade.
- Freeze drying and contact adsorption drying is not suitable for large-scale production because of high operation costs.

### 2.4 Mathematical modeling of drying curves

The moisture ratio (MR) of vegetables was obtained using the equation below:

$$MR = (M_t - M_e) / (M_o - M_e) \qquad \text{......................(1)}$$

where $M_t$ is the moisture content at anytime (kg water/kg dry solid), Mo is the initial moisture content (kg water/kg dry solid) and Me is the equilibrium moisture content of samples (kg water/kg dry solid).

Drying curves obtained were fitted to two moisture ratio thin layer models, namely Page and Wang and Singh. Simplification of the general series solution of Fick's second law generally leads to the two models.

The Page model is an empirical modification of the simple exponential model successfully used

to describe the drying characteristics of a variety of agricultural materials like red chilli, pigeon pea, carrot and okra by **Gupta et al (2002)**

The Page model is given as

$$MR = (M_t - M_e) / (M_o - M_e) = \exp(-kt^n) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where t is the drying time (hr), and k and n are constants in the model

The Wang and Singh model as is a second order polynomial model which has been used to characterize the drying kinetics of mushrooms by **Walde et al (2005)**

The Wang and Singh model is given as

$$MR = (M_t - M_e) / (M_o - M_e) = 1 + at + bt^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

where a and b are coefficients of the model and t is the drying time (hr),.

**2.5 Estimation of moisture diffusivity**

The Fick's second law of diffusion was used to estimate the effective diffusivity considering constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution **(Crank, 1975):**

$$MR = \frac{8}{\pi^2} \sum_{N=0}^{\infty} \frac{1}{(2N+1)^2} \exp\left[\left(-(2N+1)^2 \pi^2 Dt\right)/4L^2\right] \ldots\ldots\ldots\ldots..(4)$$

where D is the effective diffusivity ($m^2/s$), L is the half-thickness of the slice samples (m) and n is a positive integer. This equation (4) can be simplified by taking the first term of series solution:

$$MR = (8/\pi^2) \exp(\pi^2 Dt/4L^2) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

# Chapter 3

# EXPERIMENTAL SETUP

## 3.1 Schematic representation of fluidized bed drier

The setup is a tapered fluidized bed drier consisting of Air Compressor, Air Distributor, Heater, Inlet Air Temperature Sensor, Tapered Bed, Outlet Air Temperature Sensor

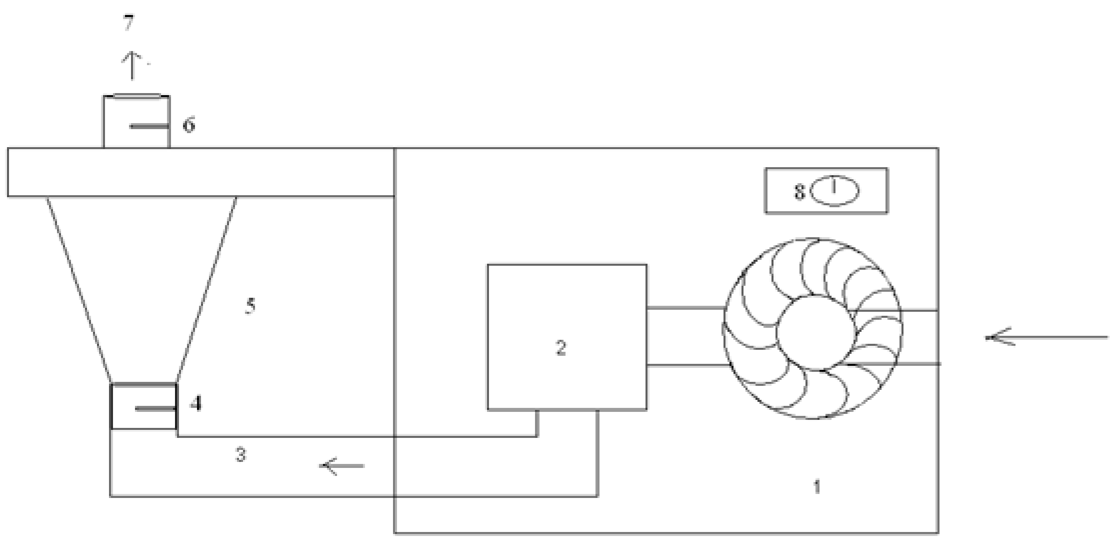


Figure 3.1 Apparatus in the set-up: 1 Air Compressor; 2 Heater; 3 Air inlet to the bed; 4 Inlet air temperature sensor; 5 Tapered Fluidized Bed; 6 Outlet Hot Air Temperature Sensor; 7 Hot Air outlet; 8 Timer.

## 3.2 Tapered Fluidized Bed Dryer

The bed is shaped like a truncated cone with bottom diameter is **12.1 cm** where as the top diameter is **21.96 cm**. The reactor height is **20 cm**. The tapered angle is 14°.

The gas distributor was 2mm thick with 2mm perforations. A fine wire mesh of 0.2mm openings was spot welded over the distributor plate to arrest the flow of solids from the fluidized bed into the air chamber. Air from the blower was heated and fed into the air chamber and into the fluidization column. The electrical heater consisted of multiple heating elements of 2 KW rating. The timer is provided in which time can be maintained from 0- 80 min.

### 3.3 Temperature controller

A temperature controller, provided to the air chamber, facilitated the control of air temperature to ± 0.5° C, for the operating range of 40-110° C.

### 3.4 Air movement

The selection and sizing of a fan to move air through a dryer is very important. The major resistance to the flow of air comes from the grain bed. The pressure drop through the bed support is of lesser effect, particularly for deep beds. The pressure drop across a grain bed is a function of the air velocity and the grain itself

# Chapter 4

# MATERIALS AND METHOD

## 4.1 Materials

Fresh green peas (*Pisum Sativum)*, Potato (*Solanum Tuberosum*) were used. The peas were spherical in shape whereas the potato were cut into a cuboid shape of size $2 \times 1 \times 0.5$ cm

Air at a temperature of 26 ºC ($\rho$ = 1.178 kg $m^{-3}$ and $\mu = 1.8\times10^{-5}$ kg $m^{-1}s^{-1}$) used as the fluidizing medium.

## 4.2 Method

A fluidized-bed was used for the drying of all samples. The fluidized bed dryer was connected to a heat pump dehumidifier system. The drying conditions of 50 °C, 60 °C, 70 °C, were set by the temperature controller in the heat pump dehumidifier system, and the drying set-up was run for 10 minutes to achieve steady state conditions of drying before material introduction. The hot air velocity passing through the material bed was kept at a constant value of 3.8 $ms^{-1}$ for a single set experiment, it was also changed by flow control valves for required three levels of 0.975, 1.95, 2.875 $ms^{-1}$ for drying experiments. Samples were taken out at regular interval of 10 minutes from the dryer for taking the readings of weight reduction and changes in volume.

# Chapter 5

# RESULTS AND DISCUSSIONS

## 5.1 Results

### *5.1.1 Scope of the experiment*

*Parameters*: Four parameters (time, velocity of air, material of solid and temperature of air) are represented in Table 1.

*Application of Walde Equation*: The observations have been applied to Walde Equation (equation 3) and the constants 'a' and 'b' with $R^2$ and RMSE have been calculated within experimental limits.

*Application of Page Equation*: The observations have been applied to Page Equation (equation 2) and the constants 'k' and 'n' with $R^2$ and RMSE have been calculated within experimental limits.

*Application of Fick's second Law of Diffusion*: The observations have been applied to Fick's second Law of Diffusion (equation 5) and the constants 'k' and Diffusivity, 'D' with $R^2$ and RMSE have been calculated within experimental limits.

*Correlation plots*: By changing one variable at a time and keeping the rest constant, a correlation has been developed; and the calculated and experimental values were compared.

(All iterations have been performed using the 'Trust-Region Algorithm' in Matlab 7 ®)

Table 5.1 enlists the variation of parameters that were employed during the course of the experimental work.

**Table 5.1: Scope of the Experiment**

| Sl. No | Material | Temperature ( ºC) | Velocity($ms^{-1}$) | Time(min) |
|---|---|---|---|---|
| 1. | Peas | 50 | 3.8 | 30 |
| 2. | | 60 | 3.8 | 30 |
| 3. | | 70 | 3.8 | 30 |
| 4 | | 60 | 3.8 | 30 |
| 5 | | | 2.85 | 30 |
| 6 | | | 1.9 | 30 |
| 7 | | | 0.95 | 30 |
| 8 | | | 3.8 | 10 |
| 9 | | | | 20 |
| 10 | | | | 30 |
| 11 | | | | 40 |
| 12 | | | | 50 |
| 13 | Moong | 50 | 3.8 | 30 |
| 14 | | 60 | | |
| 15 | Potato | 50 | 3.8 | 30 |
| 16 | | 60 | | |

### 5.1.2 Observations

Table 5.2 shows the results of modeling the experimental data using Page Equation (2)

**Table 5.2: Calculating the parameters of Page Equation from our observation**

| Temperature | Flow Rate | a | b | $R^2$ | RMSE |
|---|---|---|---|---|---|
| 50 °C | 3.8 | -0.03177 | 0.0002331 | 0.9995 | 0.00938 |
| | 2.85 | -0.03266 | 0.000253 | 0.9993 | 0.01122 |
| | 1.9 | -0.03378 | 0.0002745 | 0.9997 | 0.00772 |
| | 0.95 | -0.03141 | 0.0002234 | 0.9989 | 0.0146 |
| | | | | | |
| 60 °C | 3.8 | -0.03282 | 0.0002545 | 0.9997 | 0.00762 |
| | 2.85 | -0.03089 | 0.0002142 | 0.9988 | 0.01467 |
| | 1.9 | -0.02886 | 0.0001741 | 0.9989 | 0.01406 |
| | 0.95 | -0.0278 | 0.0001486 | 0.9958 | 0.02782 |
| | | | | | |
| 70 °C | 3.8 | -0.03095 | 0.0002174 | 0.9994 | 0.01019 |
| | 2.85 | -0.03195 | 0.0002358 | 0.9984 | 0.01714 |
| | 1.9 | -0.02956 | 0.0001871 | 0.9987 | 0.01533 |
| | 0.95 | -0.02856 | 0.0001673 | 0.9992 | 0.0119 |

Table 5.3 shows the results of modeling the experimental data using Walde Equation (3)

**Table 5.3: Calculating the parameters of Walde Equation from our observation**

| Temperature | Flow Rate | k | n | $R^2$ | RMSE |
|---|---|---|---|---|---|
| 50 °C | 3.8 | 0.01111 | 1.436 | 0.9927 | 0.03657 |
| | 2.85 | 0.01365 | 1.379 | 0.9921 | 0.03764 |
| | 1.9 | 0.01426 | 1.378 | 0.9934 | 0.03463 |
| | 0.95 | 0.00873 | 1.509 | 0.9945 | 0.03207 |
| | | | | | |
| 60 °C | 3.8 | 0.01192 | 1.424 | 0.994 | 0.03324 |
| | 2.85 | 0.01002 | 1.46 | 0.9908 | 0.04095 |
| | 1.9 | 0.00849 | 1.492 | 0.9893 | 0.0442 |
| | 0.95 | 0.00711 | 1.539 | 0.984 | 0.05441 |
| | | | | | |
| 70 °C | 3.8 | 0.01141 | 1.42 | 0.9908 | 0.04067 |
| | 2.85 | 0.00886 | 1.509 | 0.9969 | 0.02428 |
| | 1.9 | 0.00908 | 1.478 | 0.9892 | 0.04439 |
| | 0.95 | 0.00773 | 1.518 | 0.9909 | 0.04076 |

Table 5.4 shows the results of modeling the experimental data using Fick's Second Law of Diffusion (5) to determine diffusivity.

**Table 5.4: Application of Fick's Second Law of Diffusion to determine diffusivity**

| Temperature | Flow Rate | k | D | $R^2$ | RMSE |
|---|---|---|---|---|---|
| 50 °C | 3.8 | 1.04 | -0.0048 | 0.9689 | 0.07537 |
| | 2.85 | 1.034 | -0.0048 | 0.9732 | 0.06944 |
| | 1.9 | 1.034 | -0.005 | 0.9749 | 0.06759 |
| | 0.95 | 1.047 | -0.0048 | 0.9644 | 0.0816 |
| | | | | | |
| 60 °C | 3.8 | 1.039 | -0.0049 | 0.9715 | 0.07232 |
| | 2.85 | 1.041 | -0.0047 | 0.9648 | 0.08023 |
| | 1.9 | 1.046 | -0.0045 | 0.9597 | 0.08558 |
| | 0.95 | 1.048 | -0.0044 | 0.9502 | 0.09593 |
| | | | | | |
| 70 °C | 3.8 | 1.038 | -0.0047 | 0.9681 | 0.07574 |
| | 2.85 | 1.038 | -0.0047 | 0.9681 | 0.07574 |
| | 1.9 | 1.043 | -0.0046 | 0.9611 | 0.08413 |
| | 0.95 | 1.043 | -0.0046 | 0.9611 | 0.08413 |

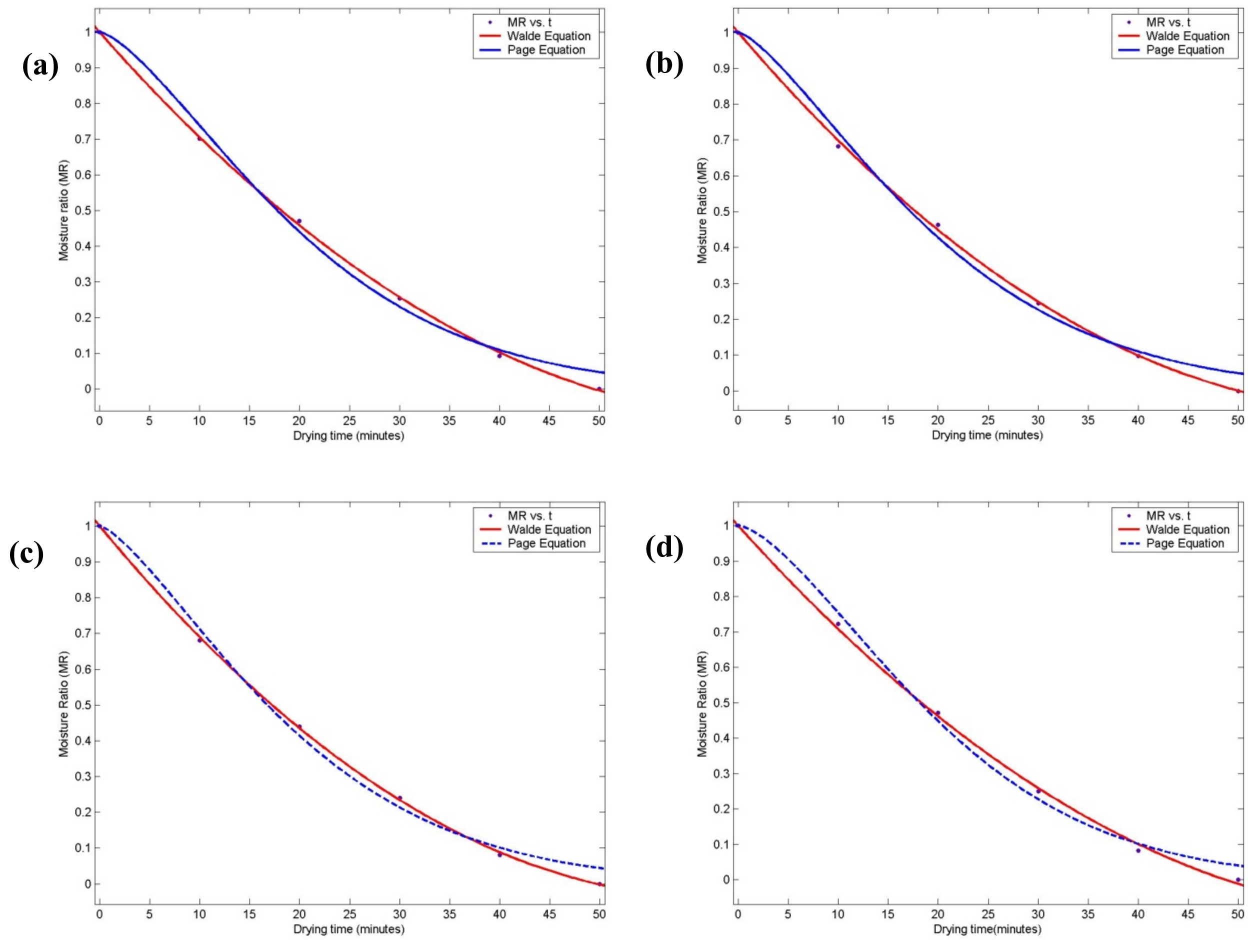


Figure 5.1: Plot of Moisture Ratio (MR) vs. Drying Time (mins) at 50 ºC fitted in accordance to Walde and Page Equations with a flow rate of (a) 3.8 $ms^{-1}$ (b) 2.85 $ms^{-1}$ (c) 1.95 $ms^{-1}$ (d) 0.95 $ms^{-1}$

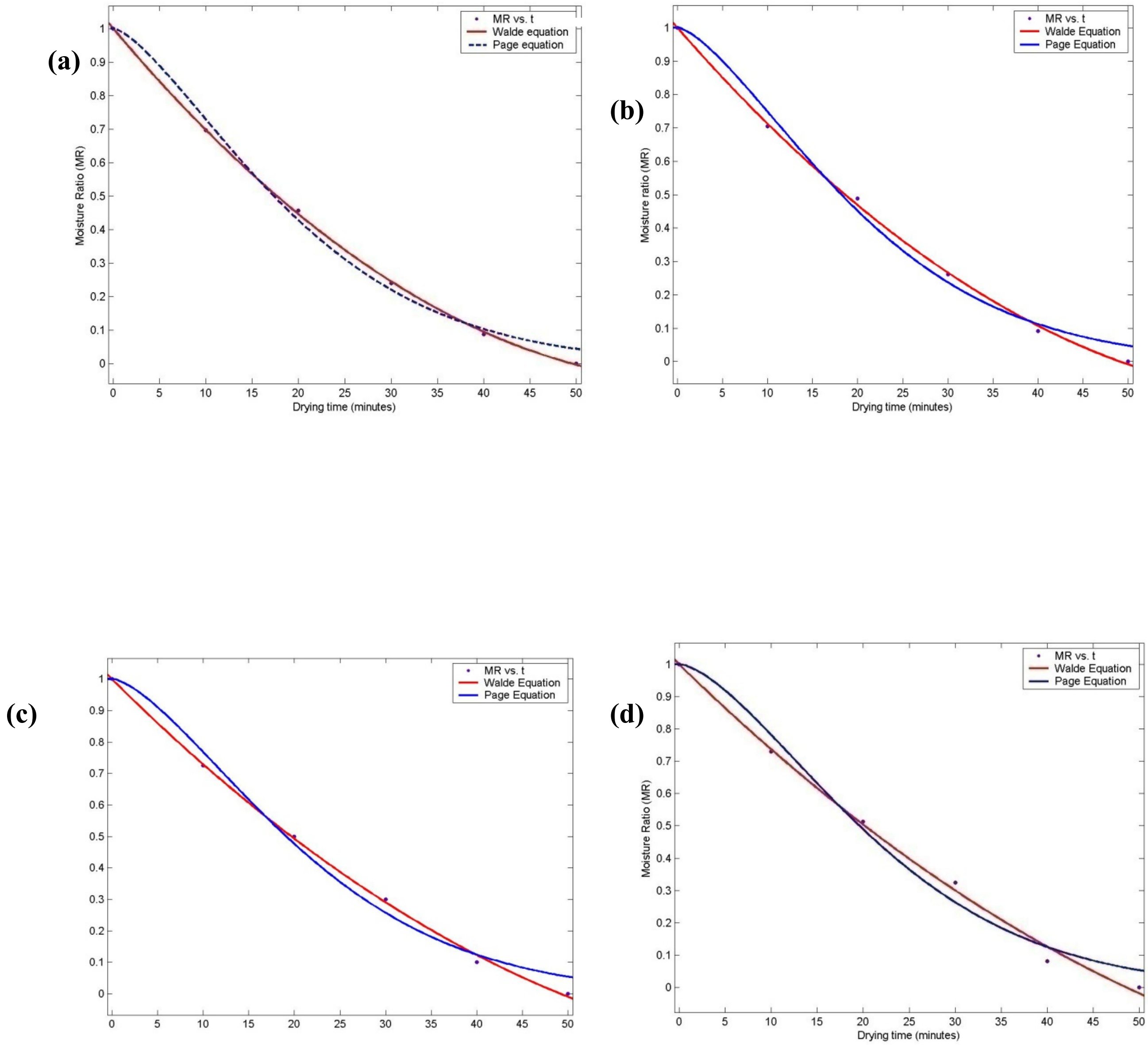


Figure 5.2: Plot of Moisture Ratio (MR) vs. Drying Time (mins) at 60 ºC fitted in accordance to Walde and Page Equations with a flow rate of (a) 3.8 $ms^{-1}$ (b) 2.85 $ms^{-1}$ (c) 1.95 $ms^{-1}$ (d) 0.95 $ms^{-1}$

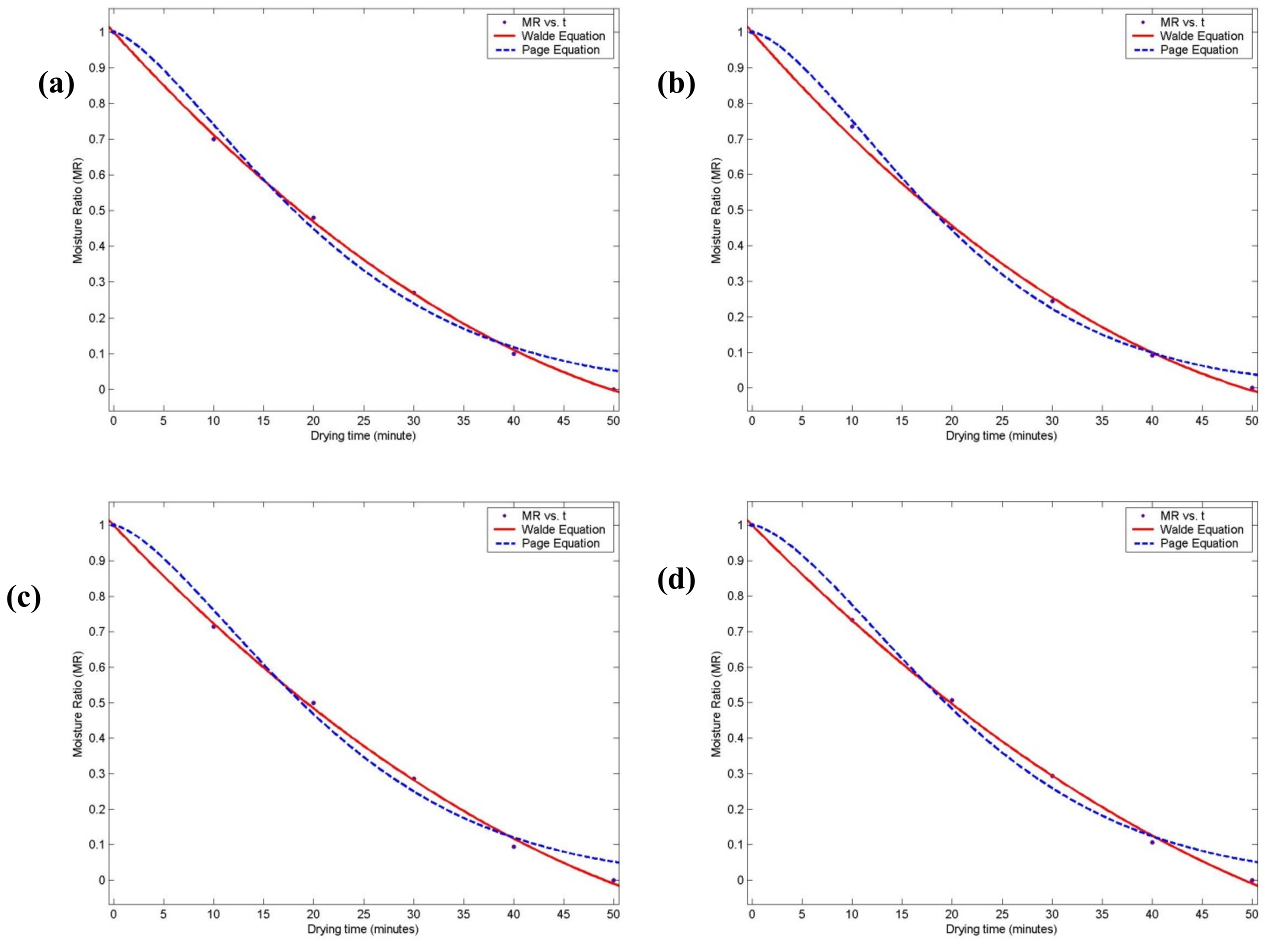


Figure 5.3: Plot of Moisture Ratio (MR) vs. Drying Time (mins) at 70 ºC fitted in accordance to Walde and Page Equations with a flow rate of (a) 3.8 $ms^{-1}$ (b) 2.85 $ms^{-1}$ (c) 1.95 $ms^{-1}$ (d) 0.95 $ms^{-1}$

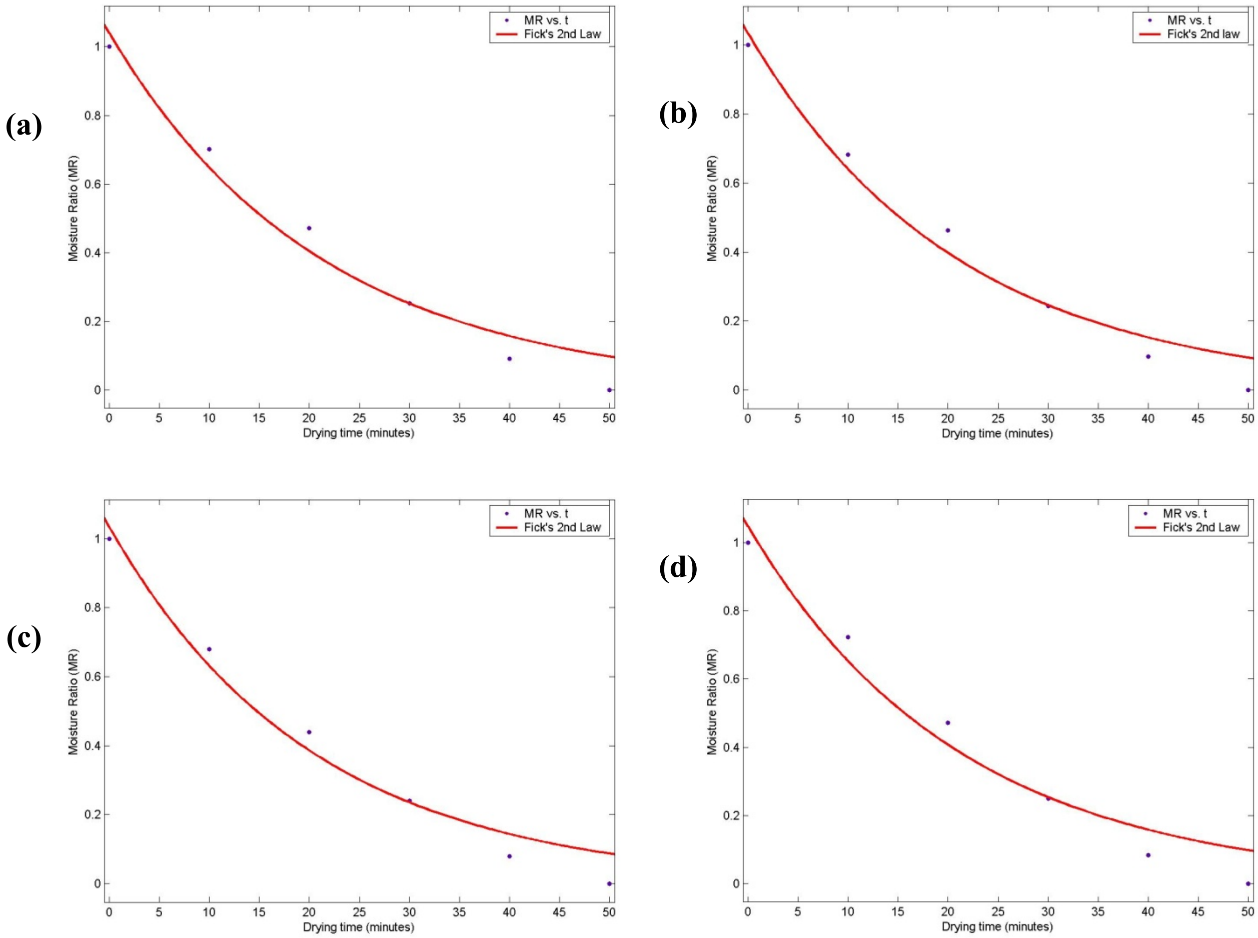


Figure 5.4: Plot of Moisture Ratio (MR) vs. Drying Time (mins) at 50 ºC fitted in accordance to Fick's $2^{nd}$ law to calculate diffusivity with a flow rate of (a) 3.8 $ms^{-1}$ (b) 2.85 $ms^{-1}$ (c) 1.95 $ms^{-1}$ (d) 0.95 $ms^{-1}$

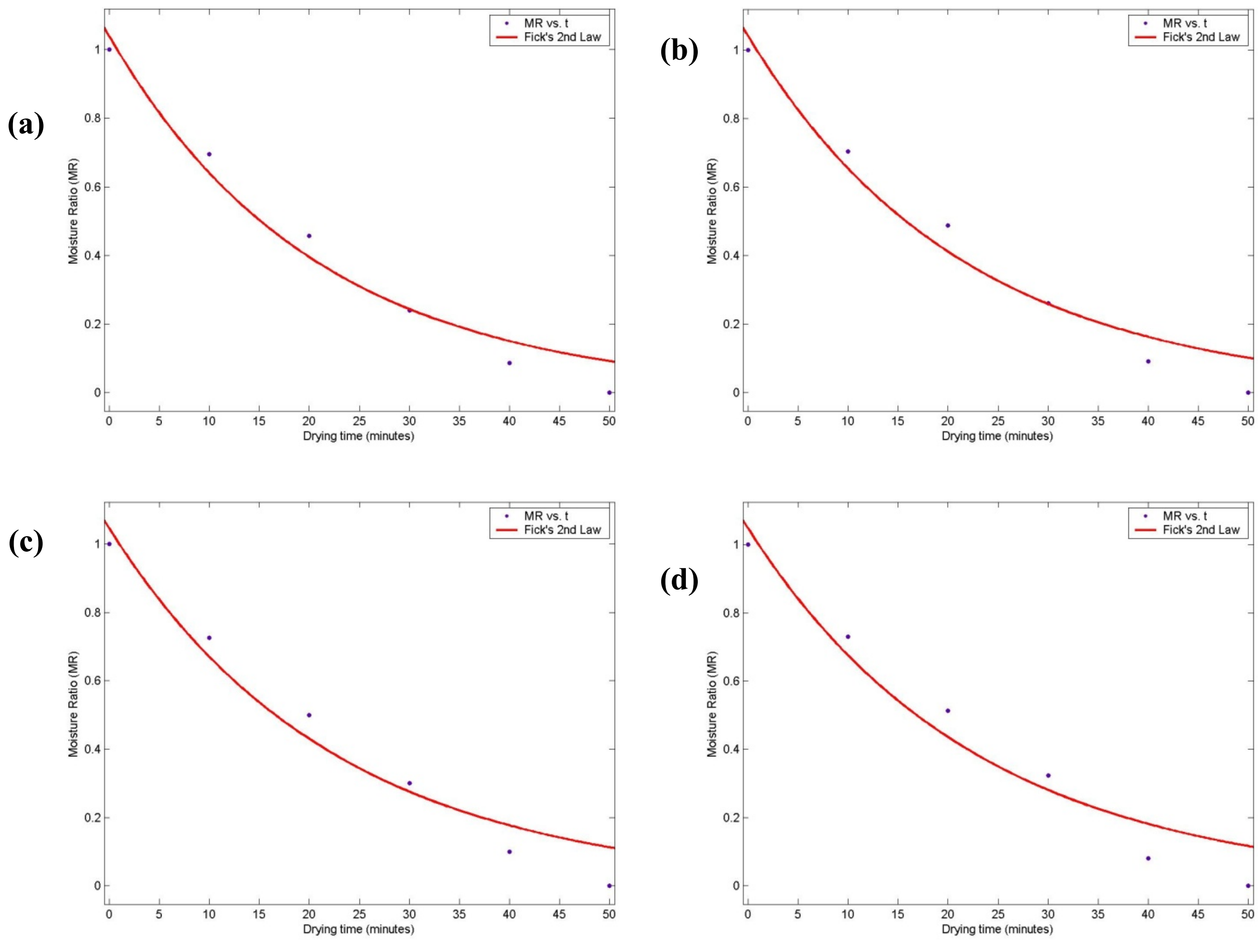


Figure 5.5: Plot of Moisture Ratio (MR) vs. Drying Time (mins) at 60 ºC fitted in accordance to Fick's 2$^{nd}$ law to calculate diffusivity with a flow rate of (a) 3.8 $ms^{-1}$ (b) 2.85 $ms^{-1}$ (c) 1.95 $ms^{-1}$ (d) 0.95 $ms^{-1}$

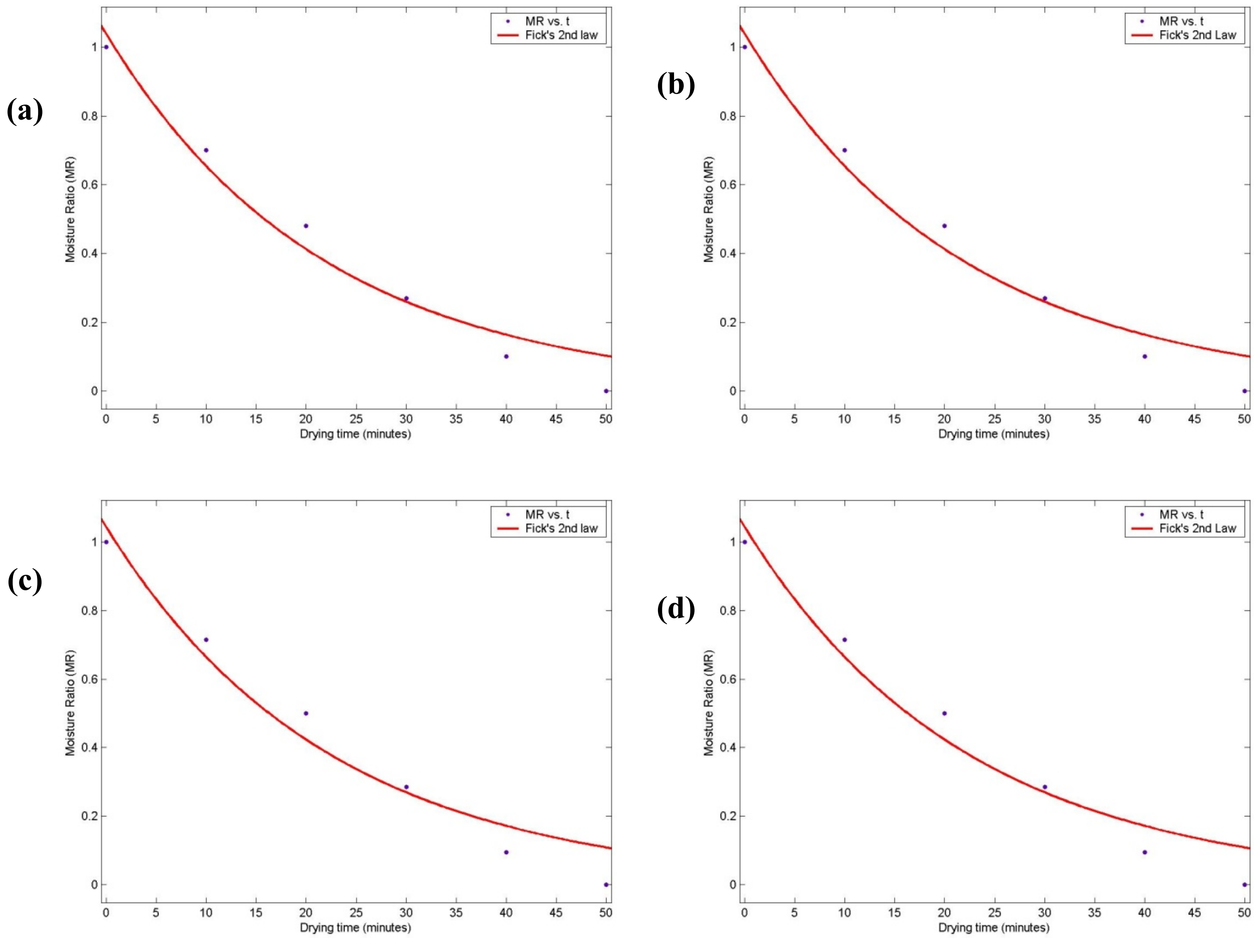


Figure 5.6: Plot of Moisture Ratio (MR) vs. Drying Time (minutes) at 70 ºC fitted in accordance to Fick's 2$^{nd}$ law to calculate diffusivity with a flow rate of (a) 3.8 $ms^{-1}$ (b) 2.85 $ms^{-1}$ (c) 1.95 $ms^{-1}$ (d) 0.95 $ms^{-1}$.

**Table 5.5: Moisture Removed (grams) vs. Time (minutes)**

| Time (minutes) | Moisture removed (grams) |
|---|---|
| 0 | 13 |
| 20 | 22.5 |
| 30 | 32.5 |
| 40 | 40 |

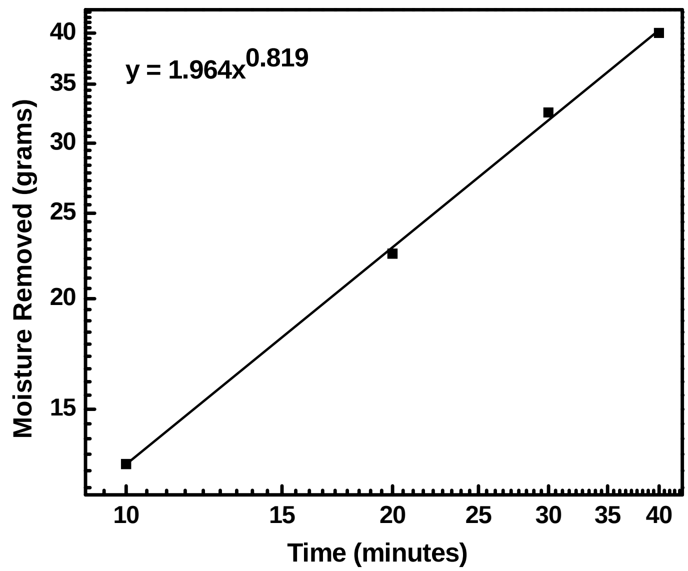


Figure 5.7: Plot showing Moisture Removed as a function of time

**Table 5.6: Moisture Removed (grams) vs. Temperature (ºC)**

| Temperature (°C) | Moisture removed (grams) |
|---|---|
| 50 | 37 |
| 60 | 40 |
| 70 | 44.5 |

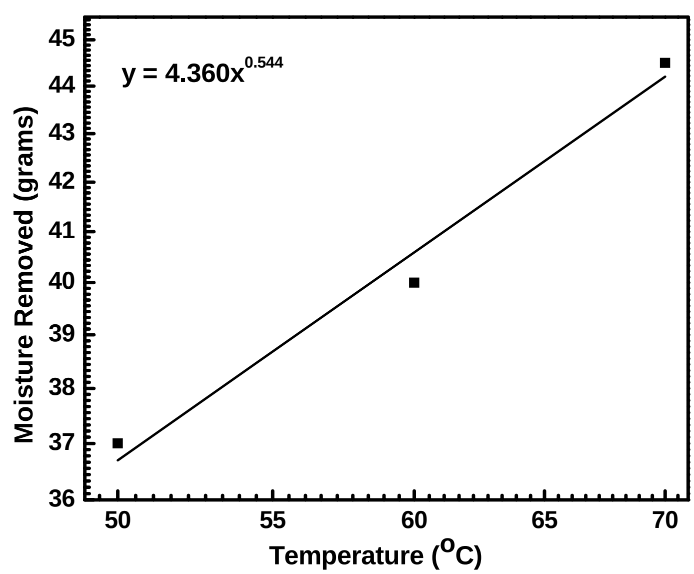


Figure 5.8: Plot showing Moisture Removed as a function of temperature

**Table 5.7: Moisture Removed (grams) vs. velocity ($ms^{-1}$)**

| Velocity ($ms^{-1}$) | Moisture removed (grams) |
|---|---|
| 0.95 | 34 |
| 1.9 | 35.5 |
| 2.85 | 40 |
| 3.8 | 42 |

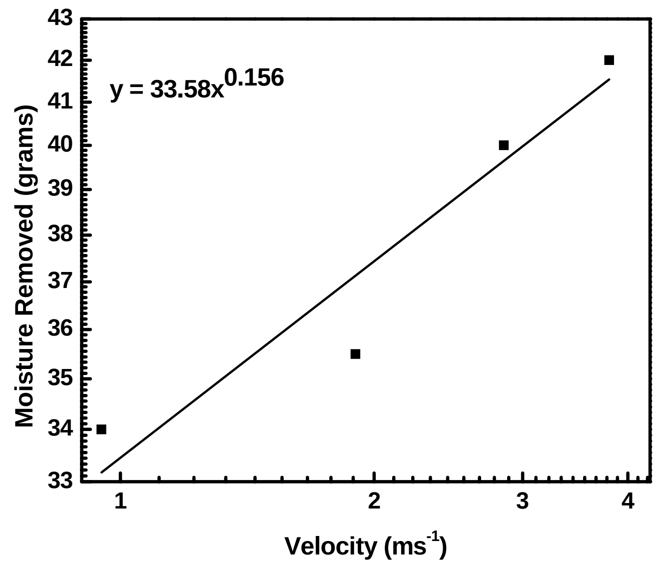


Figure 5.9: Plot showing Moisture Removed as a function of velocity of air flow.

**Table 5.8: Moisture Removed (grams) vs. density (g $cm^{-3}$)**

| Material | Density (g $cm^{-3}$) | Moisture Removed (grams) |
|---|---|---|
| Potato | 1.08 | 52 |
| Moong | 1.03 | 46 |
| Peas | 1.05 | 44.5 |

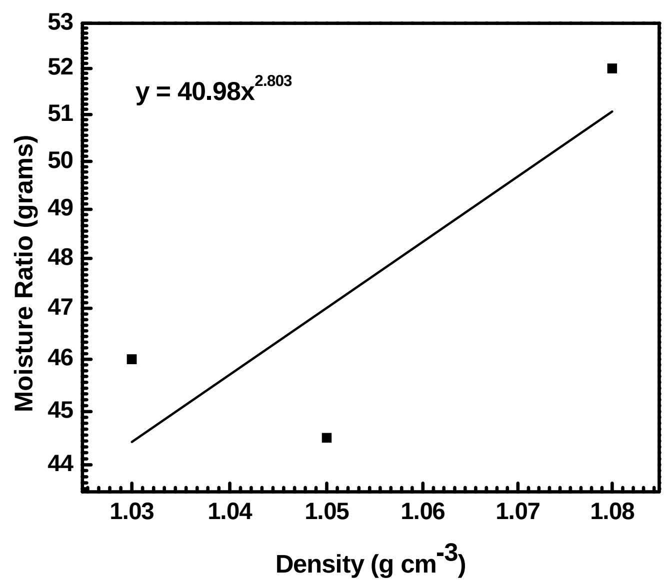


Figure 5.10: Plot showing Moisture Removed as a function of density

**Table 5.9: Observed Data & Comparison of Calculated Value of Moisture Ratio 'MR' with experimental 'MR' value**

| Time (minutes) | Temperature (°C) | Velocity ($ms^{-1}$) | Density ($g\ cm^{-3}$) | K | MR (experimental) | MR (calculated) | % deviation |
|---|---|---|---|---|---|---|---|
| 10 | 60 | 2.85 | 1.05 | 82.620 | 13 | 12.84839 | 1.16626 |
| 20 | 60 | 2.85 | 1.05 | 145.75 | 22.5 | 22.91271 | -1.83427 |
| 30 | 60 | 2.85 | 1.05 | 203.16 | 32.5 | 32.13922 | 1.110083 |
| 40 | 60 | 2.85 | 1.05 | 257.14 | 40 | 40.86057 | -2.15141 |
| 50 | 60 | 2.85 | 1.05 | 308.71 | 44 | 49.22454 | -11.874 |
| 40 | 50 | 2.85 | 1.05 | 232.86 | 37 | 36.93273 | 0.181823 |
| 40 | 60 | 2.85 | 1.05 | 257.14 | 40 | 40.86057 | -2.15141 |
| 40 | 70 | 2.85 | 1.05 | 279.63 | 44.5 | 44.50567 | -0.01275 |
| 40 | 60 | 0.95 | 1.05 | 216.43 | 34 | 34.27849 | -0.81909 |
| 40 | 60 | 1.9 | 1.05 | 241.30 | 35.5 | 38.29576 | -7.87538 |
| 40 | 60 | 2.85 | 1.05 | 257.14 | 40 | 40.86057 | -2.15141 |
| 40 | 60 | 3.8 | 1.05 | 269.02 | 42 | 42.78384 | -1.86627 |
| 40 | 60 | 2.85 | 1.08 | 278.28 | 52 | 44.28512 | 14.8363 |
| 40 | 60 | 2.85 | 1.03 | 243.64 | 46 | 38.67611 | 15.92151 |
| 40 | 60 | 2.85 | 1.05 | 257.14 | 44.5 | 40.86057 | 8.178505 |

$K = (\text{time})^{0.819}(\text{temperature})^{0.544}(\text{velocity})^{0.156}(\text{density})^{0.2803}$

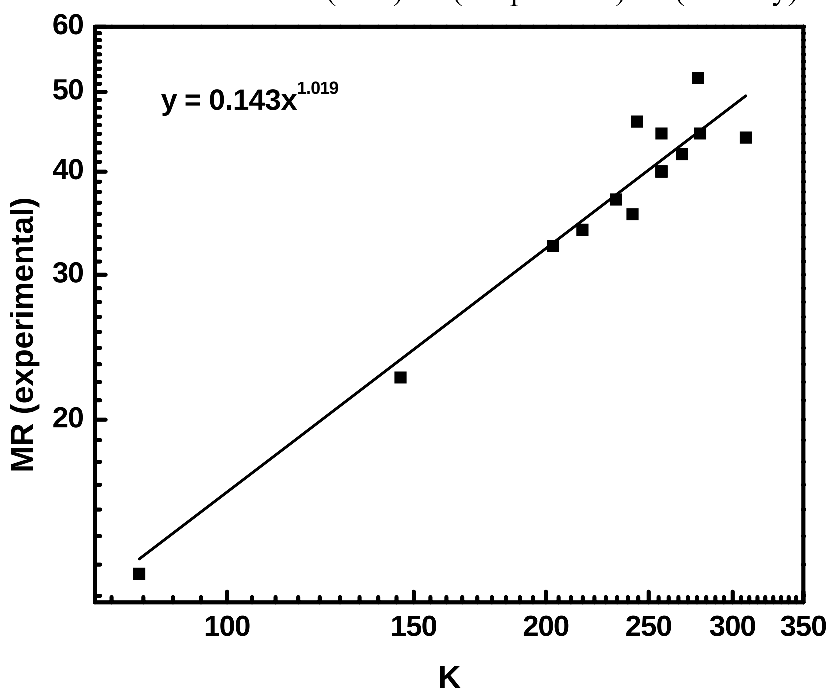


Figure 5.11: Correlation plot of moisture ratio (MR) vs. system parameters

$$MR=0.143[(\text{time})^{0.819}(\text{temperature})^{0.544}(\text{velocity})^{0.156}(\text{density})^{0.2803}] \quad \ldots\ldots\ldots\ldots\ldots (6)$$

### 5.2 Discussion

There have been certain deviations in the calculated value from the experimental values because of the shortcomings like:

1. The velocity controller in the drier is not accurate enough.
2. The temperatures of the solid falls down when we removed it to take the weight reading.
3. The atmospheric moisture changes from day to day, thus the mass transfer rate of moisture does not remain constant on all days even if our parameters were kept constant.
4. It was not possible to cut potatoes into perfect cuboids.
5. The peas obtained do not have uniform initial moisture all the time and they vary greatly in their sizes.
6. Finally, human errors might have come up when taking the readings.

# Chapter 7

# CONCLUSIONS

The following are the findings of the present studies:

1. Walde's and Page's correlations for drying efficiency were found to be applicable over a wide range of parameters with errors within experimental limits.
2. An increase in air temperature increases significantly the drying rate for all the materials. This increase in the constant drying rate is attributed to the increase in surface temperature of the particle resulting in higher surface humidity and an increased evaporation from the surface.
3. An increase in gas velocity rate increases the drying rate due to a decrease in gas film resistance surrounding the particle.
4. The solids initial moisture content influences the drying rate, Solids with high initial moisture content will have less dry solids i.e., fewer number of particles, and have reduced drying rate per unit weight of initial charge.
5. It was observed that drying rate reduces with time or with the reduction of moisture content the product's moisture content reduces over time
6. A correlation was found between the moisture ratio and the parameters which gives results comparable to experimental values and can be applied to pilot studies and even industries.

## References


- Abid, M.; Gibert, R. and Laguerie, C., "An experimental and theoretical analysis of the mechanisms of heat and mass transfer during the drying of corn grains in a fluidized bed," *International Journal of Chemical Engineering,* 1990, **30,** 632–42.
- Analia, L. and Gaston, A., "Wheat drying kinetics: Diffusivities for sphere and ellipsoid by finite elements", *Journal of Food Engineering,* 2002, **52,** 313 - 322.
- Białobrzewski, I.; Zielin´ska, M.; Mujumdar, A. S. and Markowski M, " Heat and mass transfer during drying of a bed of shrinking particles – Simulation for carrot cubes dried in a spout-fluidized-bed drier ", *International Journal of Heat and Mass Transfer* 2008, **51,** 4704–4716.
- Chandran, A. N; Subba R. S and Varma Y. B. G, "Fluidized bed drying of solids", *AIChE J* 1990, **36**, 29–38.
- da Silva, W. P.; Precker, J. W. and de Lima, A. G. B, "Drying Kinetics of Lima Bean (Phaseolus lunatus L.)"- Experimental Determination and Prediction by Diffusion Models , *International Journal of Food Engineering,* 2009, **5**¸ 1-19
- Davidson, J. F.; Clift, R. and Harrison, D.; "Fluidization of vegetables", *Academic press, London*, 1985, p.331.
- Genga F.; Xub D.; Yuana Z. and Yanb Y. "Numerical simulation on fluidization characteristics of tobacco particles in fluidized bed dryers", *Chemical Engineering Journal* 2009, **150,** 581–592
- Garnavi, L.; Kasiri, N. and Hashemabad, S., "Mathematical modeling of a continuous fluidized bed dryer", *International Communications in Heat and Mass Transfer* 2006, **33**, 666–675
- Hajidavaloo, E. and Hamdullahpur, F "Thermal analysis of a fluidized bed drying process for crops. Part 2: Experimental Results", *International Journal of Energy Research* 2000, **24**, 809 –820.
- Kunii, D. and Levenspiel, O., *Fluidization Engineering (Second edition) Butterworth-Heinemann, Sydney, Austarlia* 1977.
- Ozbey, M. and Soylemez M. S. "Effect of swirling flow on fluidized bed drying of wheat grains", *Energy Conversion and Management* 2005, **46**, 1495–1512

- Palancz, B.,“A mathematical model for continuous fluidized bed drying”, *Chemical Engineering Science- Elsevier*, 1983
- Satish, S. and Pydi S. Y. “Modeling of a continuous fluidized bed dryer using artificial neural networks”, *International Communications in Heat and Mass Transfer* 2005, **32,** 539–547
- Sobukola, O. “ Effect of Pre-Treatment on the Drying Characteristics and Kinetics of Okra” *International Journal of Food Engineering,* DOI: 10.2202/1556-3758.1191
- Srinivasa, C.; Kannan, P.; Thomas, P. and Varma Y. B. G. “Drying of Solids in Fluidized Beds” *Industrial & Engineering Chemistry Research*, 1994, **33,** 363–370
- Tasirin, S. M.; Kamarudin, S. K.; Jaafar, K. and Lee K. F. “The drying kinetics of bird’s chillies in a fluidized bed dryer”, *Journal of Food Engineering* 2007, **79**, 695–705
- Thomas, P. P.; and Varma, Y. B. G, “Fluidized bed drying of granular food materials”, *Powder Technology*, 1992, **69**, 213–222.
- Volk W., *Applied Statistics for Engineers (Second Edition) McGraw-Hill, Inc, USA*, 1969, p. 237 and p. 336
- Watano, S.; Yeh, N. and Miyanami, K., “Drying of granules in agitation fluidized bed,” ‘*Journal of Chemical Engineering, Japan* 1998, **31,** 908–913.

# APPENDIX

**Temperature = 50 ºC**

| | Flow Rate = 3.8 m/s | | Flow Rate = 2.85 m/s | | Flow Rate = 1.9 m/s | | Flow Rate=0.95 m/s | |
|---|---|---|---|---|---|---|---|---|
| Time (minutes) | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** |
| 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 0 |
| 10 | 87 | 13 | 87 | 13 | 88 | 12 | 90 | 10 |
| 20 | 77 | 10 | 78 | 9 | 79 | 9 | 81 | 9 |
| 30 | 67.5 | 9.5 | 69 | 9 | 71.5 | 8.5 | 73 | 8 |
| 40 | 60.5 | 7 | 63 | 6 | 65.5 | 6 | 67 | 6 |
| 50 | 56.5 | 4 | 59 | 4 | 62.5 | 3 | 64 | 3 |

**Temperature = 60 ºC**

| | Flow Rate = 3.8 m/s | | Flow Rate = 2.85 m/s | | Flow Rate = 1.9 m/s | | Flow Rate=0.95 m/s | |
|---|---|---|---|---|---|---|---|---|
| Time (minutes) | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** |
| 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 0 |
| 10 | 86 | 14 | 87 | 13 | 89 | 11 | 90 | 10 |
| 20 | 75 | 11 | 77.5 | 9.5 | 80 | 9 | 82 | 8 |
| 30 | 65 | 10 | 67.5 | 10 | 72 | 8 | 74 | 8 |
| 40 | 58 | 7 | 60 | 7.5 | 64 | 8 | 66 | 6 |
| 50 | 54 | 4 | 56 | 4 | 60 | 4 | 63 | 3 |

**Temperature = 70 ºC**

| Time (minutes) | Flow Rate = 3.8 m/s | | Flow Rate = 2.85 m/s | | Flow Rate = 1.9 m/s | | Flow Rate=0.95 m/s | |
|---|---|---|---|---|---|---|---|---|
| | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** | **Weight (GM)** | **Moisture Lost (GM)** |
| 0 | 100 | 0 | 100 | 0 | 100 | 0 | 100 | 0 |
| 10 | 85 | 15 | 87 | 14 | 88 | 12 | 90 | 10 |
| 20 | 74 | 11 | 73 | 10 | 79 | 9 | 81.5 | 8.5 |
| 30 | 63.5 | 10.5 | 63 | 10 | 70 | 9 | 73.5 | 8 |
| 40 | 55 | 8.5 | 55.5 | 7.5 | 62 | 8 | 66.5 | 7 |
| 50 | 50 | 5 | 51 | 4.5 | 58 | 4 | 62.5 | 4 |