Numerical Modeling and Simulation of Convective Water Activity in Low Temperature Batch Drying of Cobbed Maize

BY

CHERUIYOT SAMWEL MELLY

A Thesis Submitted to the School of Engineering, Department of Mechanical and Production Engineering in Partial Fulfillment for the Degree of Master of Science in

ENERGY STUDIES (RENEWABLE ENERGY)

MOI UNIVERSITY

2021

DECLARATION

Declaration By Candidate

I give assurance that this work is my own work and was done by me. All passages and content of this thesis which was drawn from published or unpublished work has been acknowledged.

Sign:______________________________ Date:______________________

CHERUIYOT SAMWEL MELLY

TEC/PGMP/04/18

Declaration by the Supervisors

The research project has been submitted with my approval as the university supervisor.

Sign:______________________________ Date:______________________

Dr. Isaiah Etemo Muchilwa

School of Engineering

Moi University, Kenya

Sign:______________________________ Date:______________________

Prof. Eng. Augustine B. Makokha

School of Engineering

Moi University, Kenya

DEDICATION

This thesis is dedicated;

To my late father who taught me that knowledge of any kind is that which is found for its own use.

To my mother who taught me to be resilient in undertaking task which are achieved if done step by step.

To my wife for encouraging me to undertake the study and

To my loving daughters Gloria and Celine, who cheered me up when am tired.

ABSTRACT

Drying of maize grain is considered an important process in reducing aflatoxins effects on Maize Mechanical drying is recommended over natural drying during wet weather but is costly and energy intensive. Comprehensive understanding of convective water activity during grain drying is critical to the development of more efficient drying process particularly for cobbed maize. The main objective of this study was to analyse batch dehydration of cobbed maize to help understand the dynamics of low temperature processing to facilitate the development of appropriate on-farm drying technologies. The specific objectives were (i) Experimental measurements of drying characteristics and process conditions during batch drying of cobbed maize at low temperatures,(ii) Analysis of the temperature distribution and velocity field of drying air in the batch drier using CFD software (ANSYS Fluent) and (iii) Validation of drying model using experimental results from batch drying at an industrial seed processing facility. Empirical data was obtained using temperature, relative humidity, velocity and moisture content sensors. The sensors were applied within the actual cobbed maize drying operations at Kenya Seed Company Ltd. - Kitale in November 2018.The results showed drying chamber temperatures in the range of 30 - 35ºC while the relative humidity varied from 15 – 35%. The initial moisture content of the Kernels and cob were 19%wb and 38%wb, respectively, reducing to 12%wb for both components after 70hours of dehydration. Numerical modeling was performed using CFD software (ANSYS Fluent 19R1). For ease of analysis, a 2D geometrical model was developed in accordance with the actual parameters of the drying chamber that was used in the experimental analysis. ANSYS CFD-Post was applied to visualize contours, streamline and vector plots inside the drying chamber at superficial air flows of 1m/s, 5m/s and 10m/s, for scenarios with and without the product. The simulated pressure and velocity contours showed lower airflow along the walls and at the corners, consistent with the findings of other studies on non-circular geometries. Similar trends were observed at the increased airflow settings. Non-uniform airflows cause uneven dehydration which presents a challenge for optimal termination of batch operations where over-drying is avoided. The Midili model best fitted the drying kinetics of cobbed maize with R^2 and RMSE values of 0.946 and 0.0127, respectively showing good agreement between the mathematical model and the experimental data. The study concluded that the geometry significantly affects the distribution of air velocity and temperature during drying process and that Midili Model best fits on the drying curves of cobbed maize. Further research is recommended to assess the impact of moisture content, cob size and fines / shell out on batch drying kinetics.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

$\dot{m}_A$: Mass of water in the drying air.

$X_{A0,1}$: Initial Velocity of water in the drying air

$\dot{m}_s$: Mass of water in the drying material

$X_{so,1}$: Velocity of water flow in the Drying Material.

K =drying constant

sK_o = pre-exponential factor, s^{-1}

E_a =activation energy, KJ mol^{-1}

R = universal gas constant, 8.314 J mol^{-1}

T_{abs} = absolute temperature, in K.

ΔH^* = enthalpy of activation, $JMol^{-1}$

ΔS^* =entropy of activation, $JMol^{-1}$

ΔG^* =Gibbs free energy of activation, $JMol^{-1}$

k_b = Boltzmann constant, $1.38\text{x}10^{-23}$ JK^{-1}

h_p =Planck's constant, $6.626\text{x}10^{-34}$ JS.

M -Moisture content

D_{AB} - Effective diffusivity (m^2/s)

t - Time

x - Cartesian coordinate of position (m)

Lx -thickness of the cobbed maize in the direction of mass flux where the distribution of moisture will be analyzed

f is the friction factor

$j\mathcal{D}$ is the mass transfer factor

$j\mathcal{H}$ is the heat transfer factor

ρ is the mass density (kg/m^3)

p is the static pressure (pa)

U is the velocity vector (m/s),

S_M is the momentum source (kg/m^2s^{2})?

μ is the coefficient of dynamic viscosity (Kg/m/s),

The superscript τ denotes the transpose of the tensor,

h_{tot} Is the specific enthalpy (m^2/s^2);

S_E Is the energy source (Kg/ms^3);

T is the temperature (K);

λ is the thermal conductivity (Kgm/s^3/K),

t is the time (s),

ρ_k is the turbulence production due to viscous and buoyancy forces (Kg/m/s^3),

μ_t is the turbulent viscosity (Kg/m/s,)

ε is the turbulence dissipation rate (m^2/s^3) and?

κ is the turbulence kinetic energy per unity mass (m^2/s^2)

Rv = viscous resistance

Ri = inertial resistance

U = Viscosity

ρ =Density

$\emptyset =$ Spherical of the particle making the media($\simeq 0.75$)

$e =$ Porosity of medium

$D =$ Diameter of the particle

$V =$ Average velocity

CHAPTER ONE

INTRODUCTION

1.1. Background and Motivation

Drying is a process of dehydrating a product so that the moisture is not enough to support microbial activity after harvest. Post-harvest losses have been reported due to deterioration in quality. During the early years of 1900s, efforts were made to understand some of the chemical and physical changes that occur during drying operations and develop methods of preventing undesirable quality losses. Drying is inherently a cross and multidisciplinary area due to the need for optimal fusion of transport phenomena and materials science to produce a dehydrated product of specific quality (Mujumdar & Zhonghua, 2008).

It is imperative that different types of dryer design and models make it difficult in designing despite the industrial importance of the drying processes. These operations are still based on empirical and experimental techniques.

The drying rate depends on air flow and its velocity. It is therefore very important to investigate these variables for proper design of a drying system. However, to get these variables it is very challenging during drying since one requires various sensors to be installed in varied locations of air flow (Xia & Sun, 2002).

Optimizing existing drying technologies or coming up with novel technological concepts requires simultaneous drying analysis. They include experimental and numerical methods. These methods aim in creating explicit means of improving and dealing with complexities accompanying the technologies (Defraeye, 2014).

Typically, a full-scale design and optimization is necessary but not always feasible as an alternative theoretical approach for predicting the behavior of a drying system on small scale mode. A widely acceptable and emerging technique for numerical simulation of such system is computational fluids dynamics (CFD).

It has been proven as an effective computational tool for predicting the behavior of heat and mass transfer phenomena occurring in multi component system with one or more phases.

1.2. Statement of the Problem

Maize is grown by many Kenyans for subsistence and commercial purposes. There has been an increase in post-harvest losses due to unpredictable weather patterns during harvesting of crops. People tend to wait for moistures which have capabilities of shelling immediately. This has led to the emergence of the effect of Mycotoxins on the health of people consuming the Maize. Many deaths have been attributed to the effect of Mycotoxins in Kenya. Many studies have been done to address this.

Drying is one of many ways of reducing the post-harvest losses. However, it has presented a challenge to small scale farmers on deciding at what stage of the crop do they dry; is it at the time they are physiologically mature or at the time they are dry? Studies from literature have concentrated on the drying of maize after shelling which presents a challenge to small scale farmers who will wait for the crop to dry to a level with shelling capabilities. Empirical studies have only been done on the grain drying.

Shelling of cobbed maize requires low moistures on the cob. This will require the maize to be left in the farm until it attains the required moisture hence increase in postharvest losses.

For efficiency in reducing post-harvest losses, maize has to be harvested when it reaches physiological maturity of moistures of 35%. In order to store maize for a long time, drying needs to be done. Since drying of maize grain has been presented previously in several studies, this study therefore seeks to simulate effects of various variables in drying cobbed maize in order to help in designing of cheap on-farm drier.

Empirical methods have been of focus previously hence this study will come up with a numerical tool to assist in improving the drying effectiveness and efficiency. Drying of cobbed maize is an energy intensive exercise hence an effective design of drying system is important. The numerical tool which will substitute the experimental and empirical method will assist in designing an on-farm drier which makes farmers have a cheaper way of reducing and eliminating Mycotoxins.

1.3. Research Objective

The main objective of this study was to understand the dynamic characteristics in batch dryer during low temperature drying of maize on cob to facilitate the development of on-farm batch drying technologies.

Specific objectives

a. Experimental measurements of drying characteristics and process conditions during batch drying of cobbed maize at low temperatures.
b. Analysis of the temperature distribution and velocity field of drying air in the batch drier using CFD software (ANSYS Fluent).
c. Validation of drying model using experimental results.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Maize is the main staple cereal in many African countries and especially in Kenya where it accounts for about 40% of daily calories. Kenya lies within the equatorial tropics and is renowned as a world hot-spot for aflatoxins, toxic and carcinogenic compounds associated with fungal colonization of foods. Mycotoxins are highly prevalent in Kenya's food supplies (as in most African countries too). Risks for Mycotoxins contamination exist at multiple points in the maize value chain, particularly in the small-scale sector. However, contamination that occurs at the farm level cannot be reversed at later points through proper handling. For this reason, handling that reduces Mycotoxins risk is important starting at the farm level and continuing with various actors along the chain from transporters, to grain storage, to small-scale processors and mills, and others. Upgrading technology on small farms is indispensable for the success of Mycotoxins control. Rather than rely exclusively on imports indigenous solutions, including grain threshers, dryers, moisture detectors, traditional cold rooms and mud or metal silos, for example, could be optimized to combat the Mycotoxins menace and benefit local enterprise and livelihoods, simultaneously. The proposed project seeks to introduce innovative grain storage and handling technology to mitigate aflatoxins contamination in African postharvest chains.

2.2. Theory of Drying

Drying has two basic states; diffusion of internal moisture to the surface of the kernel from the cob and the removal of external moisture by air flowing around the kernel. Vapor pressure is increased internally within the kernel which causes moisture to diffuse through the mini pores of the seed coat.

The grain temperature which largely establishes the rate of diffusion must be controlled in order not to exceed the maximum rate which would result in damage.

Removal of the exterior moisture for a given air flow is also dependent upon air temperature

The drying of the cobbed maize involves simultaneous transfer of heat and moisture. The temperature of the product is increased within the cobbed maize while the heat and water exchange with the air takes place at the maize interface (Saadani, Rahmoune, Sbai, & Dafir, 2014).

The cobbed maize surface is warmer and more humid than air resulting in evaporation. Moisture from inside the cobbed maize diffuses towards the surface makes up for evaporation. The balance between evaporation and diffusion governs the water activity near the surface.

The flow characteristics are impacted by both heat and mass transfer and development of momentum, heat and mass boundary layer (Trujillo & Pham, 2006).

In order to have high quality final product, growers harvest their maize in a state which has reached physiological maturity. This allows the product to avoid exposure of climatic conditions, micro-organisms and insect attacks that could reduce its physical and physiological quality.

Reduction in the moisture content of cobbed maize alters the biological activity as well as the chemical and physical changes that occur during storage. This reduction of moisture content involves heat and mass transfer which changes the grains quality.

Drying is an important post-harvest operation for preservation of many agricultural products. The probability that the quality of the product will be lost is high if nothing is done. Drying is usually the most energy and cost intensive operation.

2.3. Drying Mechanism

The mechanism of drying is well explained by the transfer of mass and energy leading to its balance. This is explained by the law of mass and energy balances which assist in the control of the process in the drying of agricultural products. Conservation of mass and energy plays critical role in coming up with drying processes.

The figure 2-1 gives an overview of how the dryer balance

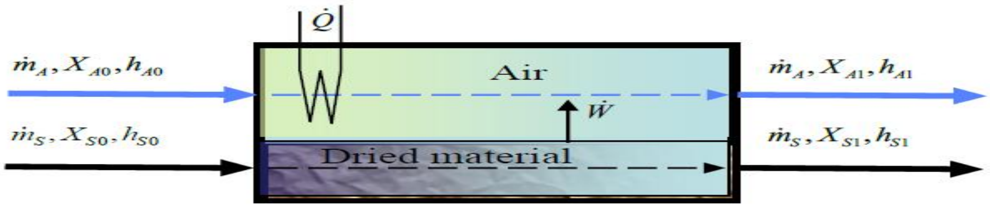

Figure 2-1: Mass balance in the drier

The equilibrium of water movement is given by the expression below:

$\dot{m}_A X_{A0} + \dot{m}_s X_{so} = \dot{m}_A X_{A1} + \dot{m}_s X_{s1}$... Equation 2-1

The mass flow rate, the amount of water removed from the system

$\dot{W} = \dot{m}_A(X_{A1} - X_{A0}) = \dot{m}_A(X_{S0} - X_{S1})$.. Equation 2-2

$Q = \dot{m}_A(h_{A1} - h_{A0}) + \dot{m}_S(h_{S1} - h_{S0})$Energy balance ....Equation 2-3

Where

$\dot{m}_A X_{A0,1}$: Water flow rate of the drying air

$\dot{m}_s X_{so,1}$: Water flow rate in the dried material

$\dot{m}_A$: Mass of water in the drying air.

$X_{A0,1}$: Initial Velocity of water in the drying air

$\dot{m}_s$: Mass of water in the drying material

$X_{so,1}$: Velocity of water flow in the Drying Material.

2.4. Selection of Dryer

There has been increase in the available driers in the market nowadays. Selecting the appropriate drying equipment is very important and it depends on the knowhow and the experience one has. Since selecting the appropriate dryer is a complex process, analysis of the drying process is very important. This complexity necessitates consideration of many factors which will contribute to decision-making.

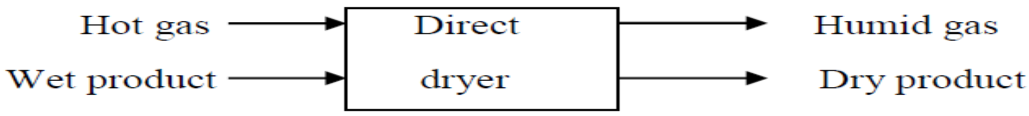

Figure 2-1: Convective drier

During drying there are two classes of processes that are encountered in practice steady state and unsteady state (batch). The difference can be found through the evaluation of the balance equations of a given system volume of a space.

Table 2-1: Classification of Dryers.

CRITERION	**TYPES** –(*) MOST COMMON PRACTICE
Mode of operation	Batch, Continuous*
Heat input	Convection, conduction, radiation, electromagnetic fields, combination of heat transfer modes, Intermittent or continuous*, Adiabatic or no-adiabatic
State of material in Drier	Stationary, Moving, agitated, dispersed
Operating pressure	Vacuum*, Atmospheric
Drying medium(convection)	Air*, Superheat steam, Flue gases
Drying temperature	Below boiling temperature*, Above boiling temperature, Below freezing point
Relative motion between drying medium and drying solids	Co-current, Counter-current, Mixed flow
Number of stages	Single*, Multi-stage
Residence time	Short (< 1 minute), Medium (1-60 minutes), Long (> 60 minutes)

Table 2-2: Check-list for selection of dryers

Physical form of feed	Granular, particulate, sludge, crystalline, liquid, pasty, suspension, solution, continuous sheets, planks, odd-shapes (small/large), Sticky, lumpy
Average throughput	Kg/h (dry/wet); continuous, Kg per batch (dry/wet)
Expected variation in throughput (turndown ratio)	Oil, Gas, Electrical
Fuel choice	
Pre- and post-drying operations (if any) For particulate feed products	Mean particle size, Size, distribution, Particle, density, Bulk density, Rehydration properties
Inlet/ outlet moisture content	Dry basis, Wet basis
Heat sensitivity	Melting point, Glass transition temperature
Drying time	Drying curves, Effect of process variables
Special requirements	Material of construction, Corrosion, Toxicity, Non-aqueous solution, Flammability limits, Fire hazards, Color/texture/aroma requirements (if any)
Foot print of drying system	Space availability for dryer and ancillaries

2.5. Drying Rates

The drying of agricultural products is different from others since they are hygroscopic (moistures are held within). The moisture is trapped in closed capillaries and pores, the water held by the surface forces as well as the unbound water held inside the cobbed maize by the surface tension of the water itself. During drying of hygroscopic materials there is always residual moisture unlike the un-hygroscopic materials which you can dry to zero moisture. When the cobbed maize is applied with heat at constant moisture content, its vapor pressure increases (Ekechukwu, 1999). This results in the movement of moisture from a position of higher pressure to low pressure. The rate of moisture movement from one region to another is proportional to the vapor pressure differences with the environment due to the cobbed maize resistance to the moisture movement. There are two main drying processes for the agricultural products which include the constant drying rate period and the falling drying rate period.

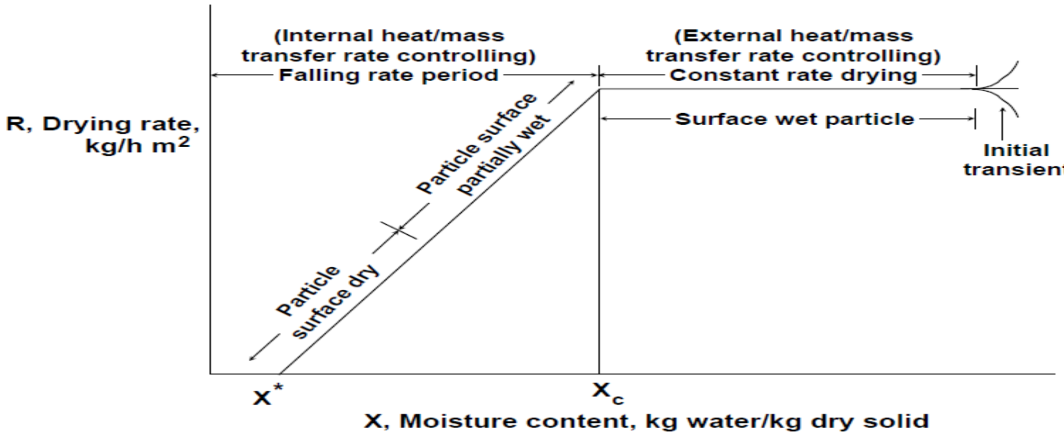

Figure 2-1: Drying process for agricultural products.

During the constant drying rate period, the drying takes place on the surface of the product due to evaporation of moisture from the free water surface. The condition of the surroundings largely contributes to the removal of moisture from the surface of the cobbed maize. At this period, the surface of the product is highly saturated with moisture with its temperature being constant and approximately equal to wet bulb. At the end of constant drying period, it is marked with reduction in the rate of moisture flow from the product due to the resistance from within the product (Ekechukwu, 1999). During this drying period, the environmental factors are not contributing to the rate of moisture removal from the product and it defines the critical moisture content (Ekechukwu, 1999). defines critical moisture content of maize as the minimum moisture content at which the rate of free moisture moves from inside the cobbed maize to the surface is the same as the rate of moisture evaporation from the surface. When this moisture content is passed, falling drying rate period is encountered which is dependent on the rate of diffusion of moisture from inside the product to the surface and the movement of moisture from the surface.

Mathematical models and simulation tools for drying kinetics are potentially useful in understanding the factors that affect drying. Drying air flow and the temperature are the parameters which require monitoring during this operation. In addition to shrinkage rate, temperature profile provides the fundamental kinetic data required for describing drying processes of a given material (Foerster, Woo, & Selomulya, 2016). The impact of air speed and flow temperature has been found to have little significance in drying compared with altering air humidity (Defraeye, 2014)

The decrease in the product moisture content reduces the biological activities and both chemical and the physical changes that occur during the storage of the cobbed maize. The moisture reduction involves both the heat and mass transfer processes which take place concurrently. These changes have substantial change in the quality of the cobbed maize if not analyzed well. The behavior of the drying conditions determines the method(s) of drying to be applied (Corrêa, Botelho, Oliveira, Goneli, Resende, & Campos, 2011).

2.6. Investigating the Influence of Temperature on the Drying Constant and Other Considerations

The evaluation of the influence of the temperature on the drying constant is done using the Arrhenius equation as shown in the equation 2.4.

$$\boldsymbol{k = k_o \left[\frac{E_a}{RT_{abs}}\right]} \quad \text{..Equation 2-1}$$

The determination of enthalpy, entropy and Gibbs free energy of activation is done by application of the activation energy value computed using the equations as shown in the equations beow:

$$\Delta \boldsymbol{H}^{*} = \boldsymbol{E_a} - \boldsymbol{RT_{abs}} \quad \text{...Equation 2-2}$$

$$\Delta \boldsymbol{S}^{*} = \boldsymbol{R}\left[\boldsymbol{lnk} - \boldsymbol{ln}\left(\frac{k_b}{h_p}\right) - \boldsymbol{lnT_{abs}}\right] \quad \text{......................................Equation2-3}$$

$$\Delta \boldsymbol{G}^{*} = \Delta \boldsymbol{H}^{*} - \boldsymbol{T_{abs}}\Delta \boldsymbol{S}^{*} \quad \text{...Equation 2-4}$$

2.7. Water Activity

Water activity is a very important parameter in drying of materials because the physical-chemical and microbiological changes that occurs during the process directly depend on it (Giraldo-Zuniga, Arévalo-Pinedo, Rodrigues, Lima, & Feitosa, 2004).

Water activity (aw) of an agricultural product is the ratio between the vapour pressures of the product itself when a completely undisturbed balance with the surrounding air media.

The water activity increases with increase in temperature of drying air. The moisture condition of a product can be measured as the equilibrium relative humidity (ERH) expressed in percentage of the water activity. Most of the agricultural products have a water activity above 0.95 which provide sufficient moisture to support the growth of bacteria, yeast and mold. This means that water activity needs to be reduced to a point which will inhibit the growth of organisms.

Every product has a natural relationship between moisture content and water activity called Moisture Sorption Isotherm (MSI) which is defined as relationship at equilibrium between water content and equilibrium humidity of the product. The implications of water activity in drying of agricultural products related to shelf life, contamination, health, texture and taste issues hence water activity measurement is an important factor in design and process control.

From definition;

$aw = p/p*$ ……………………………..…………………..………..…..Equation 2-1

Where p is the partial vapor pressure of water in the solution and p* is the partial vapour pressure of pure water at the same temperature.

$ERH =$

$a_w x 100$……………………………………………………………………………Equation 2-2

Where ERH-Equilibrium relative humidity

At equilibrium, the relationship between water content and equilibrium relative humidity of material can be displayed graphically by moisture sorption isotherm.

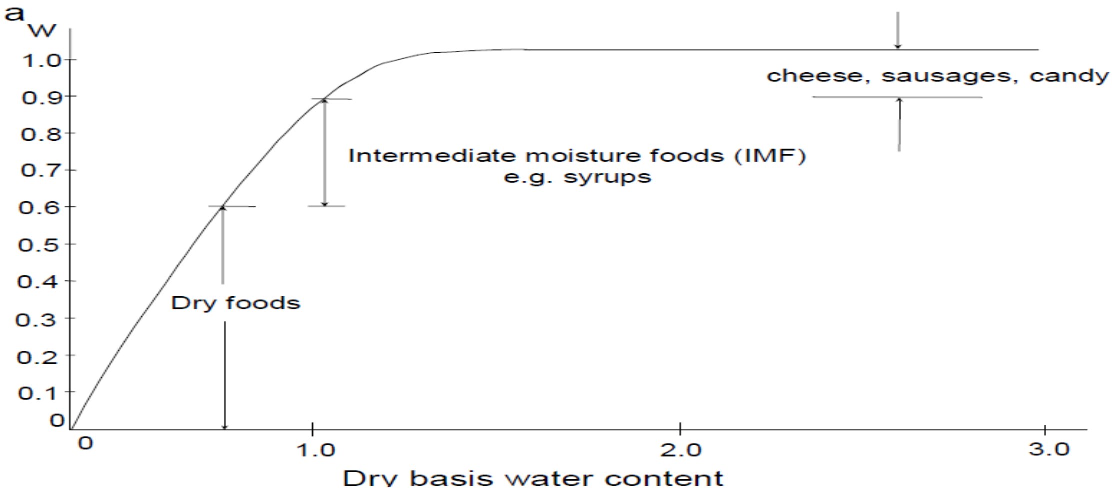

Figure 2-1: water activity of different products

2.7. Water Diffusivity

The diffusion coefficient (D_{AB}) and the mass transfer coefficient (β) are the parameters which determine the drying of most of the products. These can be obtained through experiment and the computational fluid dynamics.

The calculation of the mass transfer in any porous material during drying is normally based on equation of diffusion. The effective diffusion coefficient defines the flow of fluid inside the porous material (Akosman, 2004).

The diffusion equation is stated as

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_{AB}\frac{\partial M}{\partial x}\right) \quad \text{……………………………….…………….Equation 2-1}$$

2.8 Computational Fluid Dynamic Simulation of Drying Process.

Computational Fluid Dynamic is a research tool used to enhance the understanding of the nature of fluid dynamic. Drying is an essential process in the manufacturing industries. The drying rate is the function of the flow of air through drying product. The study of air velocity in the drying chamber is very important in order to know it's dynamic. Determination of airflow and air velocity during drying operation is very difficult to measure since it requires various sensors to be placed all several points of air flow. Due to this difficulty CFD is a tool which will aid in predicting and designing drying process.

The main advantage of CFD method in the evaluation of drying system is that it allows evaluation of the effects of drying parameters in the geometry in less time and cost. It provides detailed output which gives a better understanding of the dryer.

The fundamental principles for computational Fluid Dynamics (CFD) concepts are presented in this section. The heat and mass transfer correlation with CFD will be described in this section. Computational fluid dynamics (CFD) is a powerful numerical tool that has received wide acceptance in simulation of many processes in real life situation. It has proved to be effective Computing tool coupled with reduction in the cost of (CFD) software package.

2.8.1 Governing equations

The equation governing the flow of fluid and heat transfer is considered as mathematical formulation of the conservation laws of fluid mechanics and are called naiver – stokes equation. When the equation is applied on fluid continuum, they relate to change of a desired property of a given fluid to the external force and are considered as follows.

1. The law of conversation of mass (continuity) which state that the mass flows entering a fluid element must balance exactly with those leaving.
2. The law of conversation of momentum (Newton's second law of motion) which states that the sum of external forces acting on fluid particle is equal to its rate of the change of linear momentum.
3. The law of conversation of energy (the first law of thermodynamics), which state that of change of energy of fluid particle is equal to heat addition and the work done on the particle

By enforcing these conservation laws over discrete spatial volume in fluid domain, it is possible to achieve systematic account of the changes in mass momentum and energy as flow crosses the volume boundaries. The resulting equation can be written as:

Continuity equation:

$\frac{d\rho}{dt} + \frac{\partial}{\partial_{x_i}}(\rho u_j) = 0$……………………………………………………….Equation 2-1

Momentum equation:

$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial_{x_i}}(\rho u_i u_j) = \frac{\partial}{\partial x_j}\left[-\rho \delta_{ij+\mu\left(\frac{\partial u_j}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)}\right] + \rho g i$…………..……Equation 2-2

Energy equation:

$\frac{\partial}{\partial t}(\rho C_a T) + \frac{\partial}{\partial x_i}(p u_{jC_a} T) - \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right) = s_T$…………….……….……..Equation 2-3

There are two ways to model the density variations that occur due to buoyancy. The first is to assume that the density differentials in the flow are only required in the momentum equations and are represented by:

$\rho = \rho_{ref[I-\beta(T-T_{ref})]}$…………………….....……………………..……….Equation2-4

Finite difference techniques have difficulties in handling of complex geometries. This has led to increased use of finite element and finite volumes, which employ suitable meshing structures to deal appropriately with arbitrary geometry. Finite element can be shown to have optimal properties for some types of equations. However, only a limited number of commercial finite element packages exist, which is undoubtedly a reflection of the difficulties involved in the programming and understanding of techniques

Fortunately, such difficulties are obviated through implementation of finite volumes methods. When the governing equations are expressed through finite volumes, they form a physically intuitive method of achieving a systematic account of the changes in mass, momentum and energy as fluid crosses the boundaries of discrete spatial volumes with the computational domain. The ease in the understanding, programming and versatility of finite volumes has meant that they are now the most commonly used techniques by CFD code developers.

2.9 Modeling of Porous Media

Many large–scale processes in the food industry may have the potential grid point demands in CFD models owing to the complex geometry of the modeled structures. For example, to predict the detailed transfer processes within a cold store containing stacked products, one must mesh all the associated geometry with a complex unstructured or body fitted system, which is highly demanding and, in many cases, inaccessible task. In any case, both computational power and CFD algorithms have not yet reached such levels of maturity that these types of computations can be achieved. Therefore, other methods must be used to exploit the physical relationship that exist on a macroscopic level and sufficiently represent the dynamic flow effect that is representative of the modeled material. The porous media assumptions, which relates to the effects of particles size and shape, alignment with airflow, void fraction size and shape, alignment with airflow and void fraction on pressure drop over the modeled product, has been used in recent studies. This method basically applies Darcy's law to porous media by relating the velocity drop through the pores to the pressure drop over the material.

An extension of this law to account for most commonly encountered non-linear relationships between pressure drop and velocity is represented by the Darcy – Forchhimer equation.

$$\frac{\partial \rho}{\partial x} = -\frac{\mu}{k^{v}} + \rho C F u^{2} \qquad \text{Equation 2-1}$$

2.10. Determination of Convective Heat Transfer Coefficient

The correlation of heat and mass transfer are provided in the available CFD packages hence there is need to develop an analogy. The analogy of heat and mass transfer has been used in engineering and scientific processes. It has been proven to work experimentally.

The most commonly used analogy is Chilton –Coburn that is based empirical correction

The Chilton –Coburn analogy is expressed.

$\boldsymbol{jD = jH = \frac{f}{2}}$……………………………………..……………..Equation 2-1.

The $j\mathcal{D}$ and $j\mathcal{H}$ factor defined is defined by the equations below:

$\boldsymbol{j\mathcal{D}}= \frac{\boldsymbol{\alpha}}{\boldsymbol{\rho C\rho V}}(\mathrm{Pr})^{2/3} = \frac{\boldsymbol{Nu}}{\boldsymbol{RePr}}(\mathrm{Pr})^{2/3} = \frac{\boldsymbol{Nu}}{\boldsymbol{Re(Pr)1/3}} = \mathrm{St}\ (\mathrm{Pr})^{2/3}$………..…………Equation 2-2

$\boldsymbol{jH} = \frac{\boldsymbol{\beta}}{\boldsymbol{V}}(\mathrm{Sc})^{2/3} = \frac{\boldsymbol{sh}}{\boldsymbol{ReSc}}(\mathrm{Sc})^{2/3} = \frac{\boldsymbol{sh}}{\boldsymbol{Re(Sc)1/3}}$ ……………………………...…Equation 2-3

In the case of independent heat and mass transfer, the ratio of Sh to Nu can be obtained from the above correlations

$\mathrm{Sh} = \boldsymbol{Nu}(\frac{\boldsymbol{sc}}{\boldsymbol{pr}})^{1/3}$……………………..…..………………………………..Equation 2-4

Equation for the forced flow:

$\mathrm{Sh} = 0.332\mathrm{Re}^{1/2}\mathrm{Sc}^{1/3}$

Knowing the heat transfer factor and the mass transfer factor we can calculate the diffusion coefficient. This is important considering that drying includes both heat and mass transfer as the material receives heat and moisture loss simultaneously.

The differential equations which are solved follow the principle of energy conservation and include the continuity, momentum and energy equations.

Mass conservation equation

$\frac{\partial \boldsymbol{\rho}}{\partial \boldsymbol{t}} + \boldsymbol{\nabla} \cdot (\boldsymbol{\rho} \cup) = \mathbf{0}$……………………..…....…………..……………………Equation 2-5

Momentum conversion equation:

$\frac{\partial(\rho \cup)}{\partial \boldsymbol{t}} + \boldsymbol{\nabla} \cdot (\boldsymbol{\rho} \cup \oplus \cup) = -\boldsymbol{\nabla \rho} + \boldsymbol{\nabla} \cdot \boldsymbol{\tau} + \boldsymbol{\mathcal{S}_m}$..Equation 2-6

Where $\boldsymbol{\tau}$ is the stress tensor given by

$\boldsymbol{\tau} = \left[\boldsymbol{\nabla} \cup + (\boldsymbol{\nabla} \cup) - \frac{\mathbf{2}}{\mathbf{3}} \boldsymbol{\delta \nabla} \cdot \cup\right]$……………………………………………Equation 2-7

Energy conversation equation

$\frac{\partial(\partial \boldsymbol{h_{tot}})}{\partial \boldsymbol{t}} - \frac{\partial \boldsymbol{\rho}}{\partial \boldsymbol{t}} + \boldsymbol{\nabla} \cdot (\boldsymbol{\rho} \cup \boldsymbol{h_{tot}}) = \boldsymbol{\nabla} \cdot (\boldsymbol{\lambda \nabla} \mathbf{T}) + \boldsymbol{\nabla} \cdot (\cup \cdot \boldsymbol{\tau}) + \cup \cdot \boldsymbol{S_M}$...........Equation 2-8.

2.11. Turbulence Modeling

Discretization of the governing equations by the software ANSYS FLUENT uses an element based finite volume method, which involve discretizing the spatial domain using mesh. Meshes used to construct finite volumes conserve relevant properties such as mass, momentum and energy (Recktenwald, 2020).The variables and properties of the fluid flow are stored in the nodes (mesh vertices). A control volume is used around each mesh and the equations above are integrated over each control volume.

The description of the turbulence effects on the air flow inside the drier, the standard turbulence model is adopted because it has been widely used in most of practical engineering flows as its advantages include among others its robustness, provides accurate results and economical (Djiako, Edoun, Desmorieux, Kuitche, & Tawetsing, 2018).

The turbulence model applies the assumption that there is conservation of kinetic energy, k, and the dissipation rate, ε, along the flow regime.

$$\frac{\partial(\rho\kappa)}{\partial t} + \nabla \cdot (\rho \cup k) = \nabla \cdot \left[\left(\mu + \frac{\cup_t}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon$$ ....Equation 2-1

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla \cdot (\rho \cup \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1} P_k - C_\varepsilon \rho\varepsilon)$$ ....Equation 2-2

Turbulence modeling is use of mathematical models to predict the effect of turbulence in a flow. Turbulence flow is a common phenomenon in real life situation for example blood flow through cardio vascular system and airflow over an aircraft. CFD simulation use turbulent models to predict the evolution of turbulence. These models are modified equations that are used to predict change in the fluid flow.

The Naiver-stokes equation governs the velocity and pressure of fluid flow. In turbulent flow, velocity and pressure of the fluid flow are decomposed into a mean and fluctuating parts which leads to Reynolds-averaged Naiver stokes(RANS) equation which govern mean flow.

2.12. Flow Through Porous Media

Navier–stoke are valid only for the flow inside pores of the porous materials but its solution cannot describe the flow in the porous region (Scheidegger, 1974.Therefore, the Navier-stoke equation should be modified to describe Darcy law which is used to establish the linear relation between the velocity y and the linear of pressure p in the porous media. It defines the permeability resistance of the flow in a porous media.

$\boldsymbol{\rho}\left(\frac{\partial \mathrm{U}}{\partial \boldsymbol{t}}(\mathrm{U}\cdot\boldsymbol{\nabla})\mathrm{U}\right)-\boldsymbol{\mu}\boldsymbol{\nabla}^{\mathbf{2}}+\ \boldsymbol{\nabla}\boldsymbol{\rho}\ =\mathrm{f\ on\ }\boldsymbol{\Omega}\mathrm{x}(\mathbf{0},\boldsymbol{t})$……………………….Equation 2-1

$\boldsymbol{\nabla}\cdot\ \mathrm{U}\ =\mathbf{0}\boldsymbol{on}\boldsymbol{\Omega}\mathrm{X}(\mathbf{0},\boldsymbol{t})$……..……………………………………….Equation 2-2

Where u= u (x_t) denotes the velocity vector, p = p(x, t) the pressure field, p the constant density μ the dynamic viscosity coefficient and f represent the external body forces acting on the fluid (i.e. gravity).

$\boldsymbol{\nabla}\boldsymbol{\rho}\ =-\boldsymbol{\mu}\mathrm{Du\ in\ }\boldsymbol{\Omega}\mathrm{X}(\mathbf{0},\boldsymbol{t})$…………………..…….…………………….Equation 2-3

Reynolds number is defined as:

$\mathrm{Re}=\frac{\boldsymbol{\rho}\boldsymbol{U}\boldsymbol{L}}{\boldsymbol{\mu}}$…………………………….…………………………..Equation 2-4

With U and L as characteristic velocity and characteristic length scale respectively

In order to characterize the inertial effects, it is possible to define the Reynolds number associated to the pores:

$\mathbf{Re}_{\boldsymbol{\rho}}=\frac{\boldsymbol{\rho}\boldsymbol{U}\boldsymbol{\delta}}{\boldsymbol{\mu}}$ …………………………….…………………………..Equation 2-5

Where δ is the characteristic pore size, whereas Darcy law is reliable for values of $Re_{\rho}<1$, otherwise it is necessary to consider a more general model, which accounts also for the inertial effects, such as:

$\boldsymbol{\nabla}\boldsymbol{\rho}=-\left(\boldsymbol{\mu}\boldsymbol{D}\boldsymbol{u}\ +\ \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\rho}\boldsymbol{C}\boldsymbol{u}\boldsymbol{I}\boldsymbol{u}\right)\mathrm{In}$

$\boldsymbol{\Omega}\mathrm{X}(\mathbf{0},\boldsymbol{t})$………………..…………………………Equation 2-6

Where C is the inertial resistance matrix

The modified Navier –stokes equation in the whole domain is found from considering the two source terms associated with the resistance induced by the porous medium (linear Darcy and inertial loss term). Hence these source terms are added to the standard fluid momentum equation as follows.

$$\boldsymbol{\rho}\frac{\boldsymbol{\partial u}}{\boldsymbol{\partial t}} - \boldsymbol{\mu}\boldsymbol{\nabla}^{2}\boldsymbol{u} + \boldsymbol{\nabla\rho} - \boldsymbol{\mu D u} - \frac{1}{2}\boldsymbol{\rho C u I u} = \boldsymbol{0 in \Omega}\mathrm{X}(\boldsymbol{0},\boldsymbol{t}) \text{ ……..……..Equation 2-7}$$

Considering a homogeneous porous media in a diagonal matrix with coeffiecients1/a, and C is also in a diagonal matrix therefore, a modified Darcy's resistance matrix should be used as follows:

$$\boldsymbol{\rho}\frac{\boldsymbol{\partial u}}{\boldsymbol{\partial t}} - \boldsymbol{\mu}\boldsymbol{\nabla}^{2}\boldsymbol{u} + \boldsymbol{\nabla\rho} = \boldsymbol{\mu D} * \boldsymbol{u in \Omega}\mathrm{X}(\boldsymbol{0},\boldsymbol{t}) \text{………………..……….Equation 2-8}$$

$$\mathrm{D}{*}{=}\mathrm{D}+ \frac{\boldsymbol{1}}{\boldsymbol{2\mu}}\cdot \boldsymbol{\rho C I u I 1} \text{…………………………..……….……….Equation 2-9}$$

Being I is the identity matrix.

It should be noted that in laminar flows through porous media, the pressure p is proportional to the velocity u and C can be considered zero (D$*= D$). Therefore, the Naiver – stokes momentum equations can be written as:

$$\boldsymbol{\rho}\frac{\boldsymbol{\partial u}}{\boldsymbol{\partial t}} - \boldsymbol{\mu}\boldsymbol{\nabla}^{2}\boldsymbol{u} + \boldsymbol{\nabla\rho} = \boldsymbol{\mu D u in \Omega}\mathrm{X}(\boldsymbol{0},\boldsymbol{t}) \text{………………....………….Equation 2-10}$$

These momentum equations are resolved by Tdyn in the case of solid, where (u.∇)$u = 0$ cannot be neglected in the modeling (i.e. high velocities), then Tdyn should resolve the following momentum equation in a fluid, instead of in a solid:

$$\rho\left(\frac{\partial u}{\partial t} + (\mathrm{u}.\nabla)\mathrm{u}\right) - \mu\nabla^{2} u + \nabla\rho = -\mu D u \;\; in\, \Omega\; \mathrm{X}(0,t) \text{…………….Equation 2-11}$$

The basic characteristic of this medium is porosity. The bulk porosity Π of a material is defined as the ratio of void volume Vv to body volume V_o

$$\mathrm{I} - \Pi - \frac{\mathrm{V_s}}{V_o}$$

Since the remaining portion V_S of the total volume of the material is in form of solid skeleton ten.

$$\mathrm{I} - \Pi - \frac{\mathrm{V_s}}{V_o}$$

For maize which has spherical shape with diameter $\partial\rho$ the porosity can be found from the relation.

$\Pi = \mathrm{I} - N_\rho \frac{\Pi \partial_\rho^3}{6}$………………………………………………..………. Equation 2-12

Where N_ρ number of particles per unit Volume.

The cubic arrangement of spheres of the same diameter is characterized by a porosity of 0.476.

Permeability is the property which gives a measure of a gas flow through a porous medium exposed to pressure difference. The superficial velocity V of fluid flow depends on permeability and pressure gradient in accorded with modified Darcy equation.

Viscous Resistance and Inertial Resistance

The viscous and inertial resistance to air flow in porous medium can be calculated using Ergun equation which gives the total pressure drop through porous medium.

Total pressure drop = viscous loss + inertial loss

$$\frac{\partial\rho}{\partial L} = \left[\frac{150u(1-e)2}{\phi i^2 D^2 e^3}\right]\mathrm{V} + \left[\frac{1.75\pm\rho(1-e)}{\phi i D e^3}\right]\boldsymbol{v}^2$$ ………………………………Equation 2-13

The viscous loss which is the first term is proportional to velocity while second term is the inertial loss (proportional to velocity squared).

Comparing the equation to the fluent expression for momentum sink, we get;

$$\frac{\partial\rho}{\partial L} = \boldsymbol{RvuV} + \frac{Ri}{2}\boldsymbol{\rho v^2}$$ ………………………………………………Equation 2-14

Which will give the rate of R_v and R_i hence

Rv=

$$\frac{150(1.e)2}{\emptyset i^{2D^{2e^3}}}$$ ………………………………………………………Equation2-15

$$\boldsymbol{Ri} = \frac{3.5(i.e)}{\emptyset i\cdot D\cdot e^3}$$ …………………………………………………………Equation 2-16

2.13 Conclusion

Drying is an important process in handling post-harvest losses. This is due to the need of achieving high quality final product. Drying is a factor of heat and mass transfer which is affected by the air flow characteristic and development of momentum.

Selection of an appropriate drier is very important in achieving effective and efficient drying system. Selecting this drier requires a complex analysis and necessitates consideration of various variables making a decision.

Drying rate is an important phenomenon when deciding which system is effective. Maize is a hygroscopic material hence having different stages of drying. The decrease in the product moisture reduces its biological activities. The method of drying should always be chosen in consideration of the behavior of the drying conditions.

The water activity, diffusion coefficient and the mass transfer coefficient are the parameters which determine drying rates of most products. These parameters have been determined in several studies and can be established using experimental and computational fluid dynamics.

Temperature, relative humidity and velocity of air have impact on drying rates. These parameters have been determined and studied experimentally.

Computational fluid dynamics is a research tool used to enhance the understanding of the nature of fluid dynamics (Kundu, Cohen, & Dowling, 2011).The study of effects of various parameters in the drying system is very important in design of drying mechanism. Determination of airflow behavior during drying operation is a difficult process since it requires various measurements at several points of air flow. Due to this difficulty, CFD is a tool which will assist in predicting the drying processes. From the studies it is preferred to be effective computing tool coupled with reduced cost in the software.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

The experiment was undertaken in an industrial seed maize drier situated at Kenya Seed Company limited in Endebess sub-county, Trans-Nzoia County. The drying system consists of three phases with 16 bins each. One bin loaded with cobbed maize was selected. Temperature and relative humidity measurements were taken to investigate the effects of process parameters in batch drier using data loggers.

Moisture content was taken at the intervals of one hour to monitor the water activity in the cobbed maize.

Analysis of velocity and temperature distribution inside the batch drier was done using computational fluid dynamics software. The CFD software used is Ansys Fluent Version R19.1

The moisture content ratios were modeled and compared with the existing mathematical models to ascertain its suitability. The best fitting model was chosen as the one describing batch drying of cobbed maize.

3.2. Drier Set Up

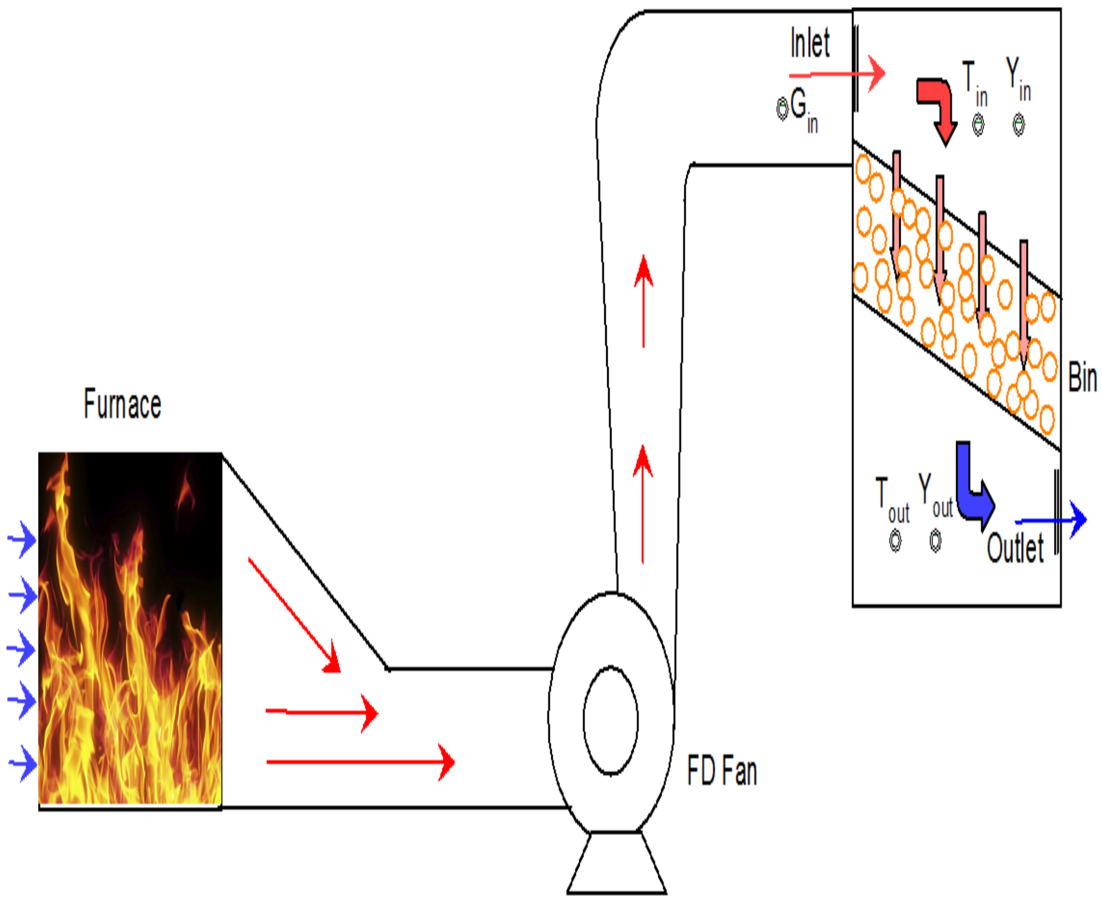

Figure 3-1: Schematic Diagram of Drying System

The drying system consists of a furnace which uses maize cobs as fuel. When the cobs have been combusted inside the furnace, hot air which is approximately at 1100°c is sucked by a primary fan with a capacity of 27,000CFM through a duct. In order to reduce the temperature of drying air to the required drying temperature, a big fan of capacity of 75,000CFM sucks atmospheric air and mixes with hot air reducing the temperature to a range of 40-50°c. This hot air is forced into the drying chamber. When the hot air enters the phlenum, there are openings which will allow air to go to the bin loaded with cobbed maize.

The drying system consists of two passes, Downward and upward air movement. The down ward air movement is where the actual drying of cobbed maize while the upward utilizes the exhaust air which it acts as pre-drying of maize.

3.3. Experimental Set Up

Temperature and relative humidity measurements were taken using data loggers and the moisture content was taken at the intervals of one hour to investigate the water activity in the cobbed maize.

The moisture content ratios were modeled and compared with the existing mathematical models to ascertain its suitability. The best fitting model was chosen as the one describing batch drying of cobbed maize.

The effectiveness of computational fluid dynamic was tested through simulation of drying using Ansys Fluent software. Air velocity and temperature dynamics in the drier were monitored and the results were compared with actual values found in experimental data. An analogy between heat and mass transfer was done to enable comparative analysis of experimental and CFD in drying of cobbed maize.

3.4: Experimental Materials

The drying bin sample was selected from 48 drying bins with cobbed maize which the process of drying had not started. The drier set up is as shown in the figure 3.2.

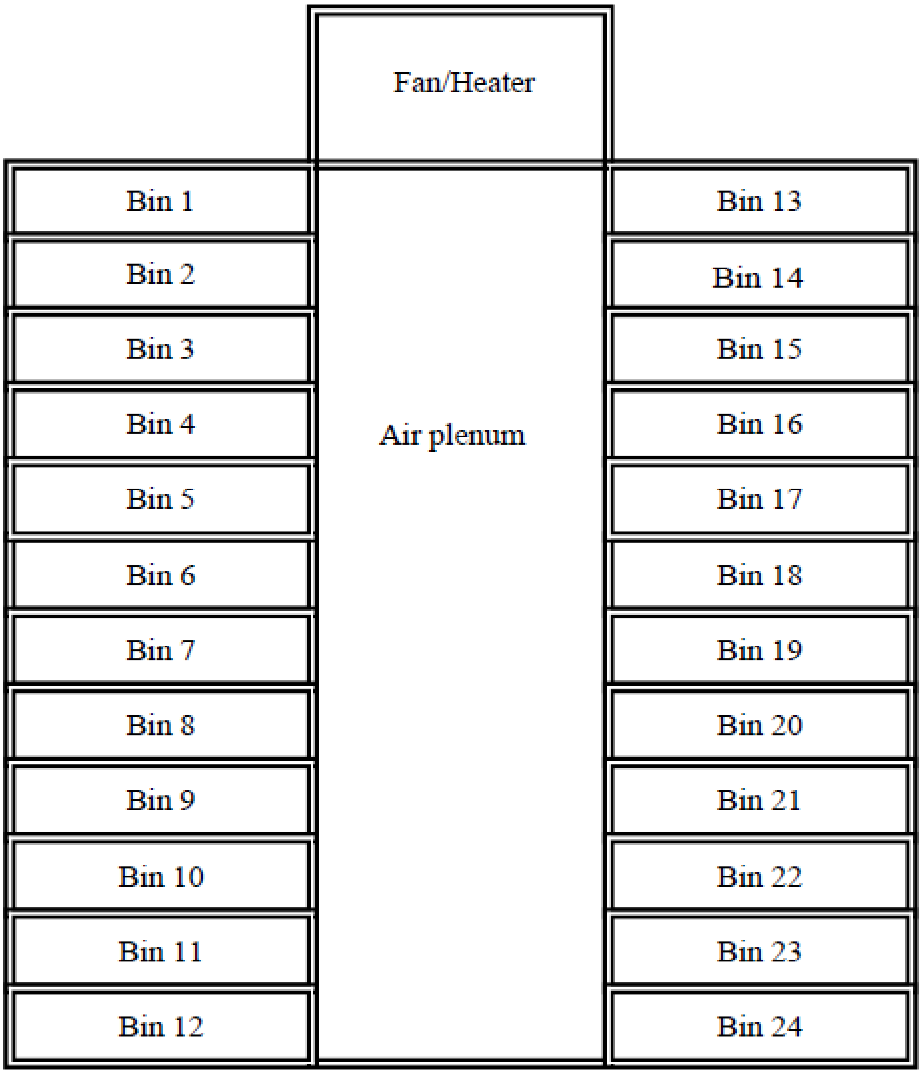

Figure 3-1 Dryer set up

The cobbed maize was loaded into the bins via conveying system. Each bin has a capacity of 800 cob bags of cobbed maize (approximately 50MT).

The fan propels heated air from the burner forcing it to the plenum as shown in the figure 3.1. The drier has two plenums (upper and lower plenum), the air moves through cobbed maize due to high pressure and exit to the lower plenum. Since there is no other opening, air will be exhausted through another bin although with low pressure and amount of heat.

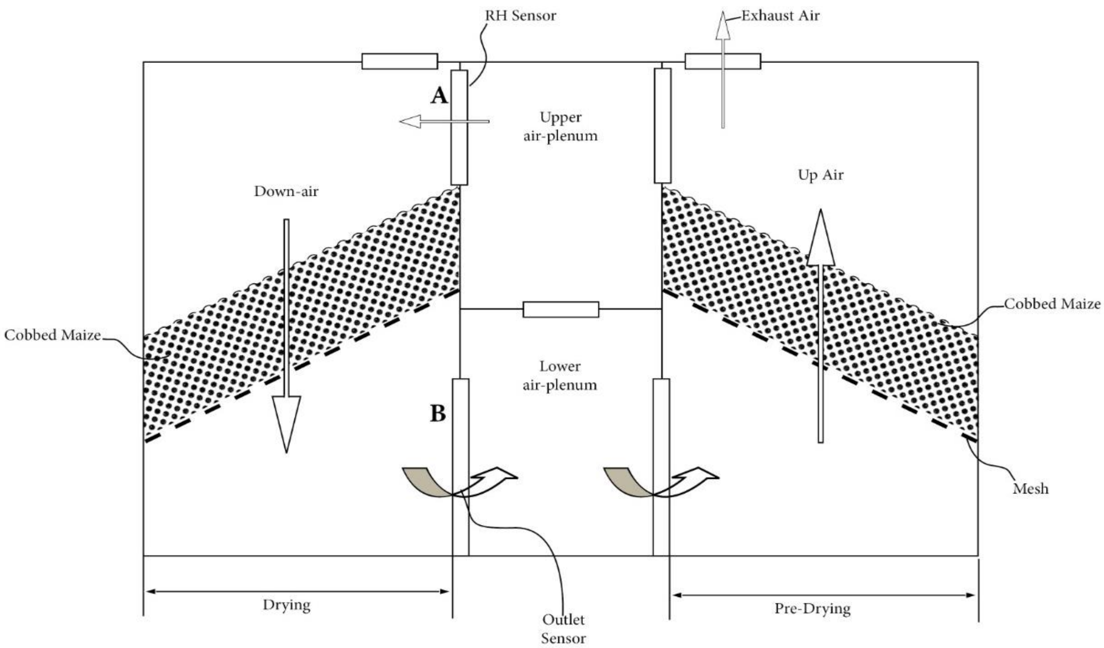

Figure 3-2: Drying System

Hot air from the furnace enters the upper air plenum at temperature of 45^0c. During the experiment, temperature and humidity sensors were put at the inlet and outlet of heated air into each selected bin.

Air will move through the cobbed maize and collects moisture exiting at point B in the lower plenum. A sensor is placed at point B to take reading of temperature and relative humidity.

3.5. Data Collection

3.5.1. Temperature and Humidity Measurement

The temperature and relative humidity of the drying air was measured using Testo 174H-Mini temperature and humidity data logger which has a temperature sensor and internal capacity humidity sensor with measuring range of 0-100% RH, -20 to 70^0C. The accuracy of the sensor is ±3%RH (2%RH to 98%RH) ± digit+3%RH/K humidity accuracy and temperature accuracy of ±0.5ºC (-20 to +70ºC)± 1 digit.

The sensors were located at air inlet and outlet in the upper air plenum and lower air plenum as indicated in figure 3.3.The data captured by the data logger sensor was read out via USB interface with the aid of comtesto software.

Figure 3-1: Temperature /humidity sensor

3.5.2. Moisture Measurement

The initial moistures of the cobbed maize were measured from the sample taken the selected bin. The moisture of the grain was taken using Agromatic moisture meter.

Table 3.1: Technical data of air velocity moisture meter

Measuring range	Display	Accuracy
1-40% Wet basis	alphanumeric 2 x 20 characters	accuracy: ISO 7700/1, OIML Tolerances for Class 1 meters)

Figure 3-2 Moisture tester

3.5.3. Air velocity measurement

Air velocity measurement was done using a digital anemometer with the following technical data:

Table 3-4: Technical data for air velocity Anemometer.

Measuring range	Resolution	Accuracy
0.80-30.00m/s	0.01m/s	±(2.0% reading+50 characters)
30.00-40.00m/s		For reference only

3.6. Experimental Procedure

The bin which has not been dried was selected amongst those loaded with cobbed maize. The temperature and relative humidity at the inlet and outlet of the drying bin was taken using the sensors. The ambient conditions were also taken.

Air flow velocity was measured at inlet and outlet using anemometer. The moisture content of the cob and the grains were taken at an interval of one hour. The moisture of the grain was measured using Agromatic Moisture Analyzer. The moisture of the cob was taken using Agromatic moisture meter. The moistures were taken at an interval of thirty minutes until such time they arrive the required minimum level.

3.7 CFD Simulation Procedure

The CFD simulation of drying seed maize in an industrial dryer was analyzed and designed using ANSYS FLUENT 19R1. For easy analysis of the drying system, the actual 2D geometry model was designed according to the actual parameters of the drying chamber that was used in the experimental analysis.

The flow through the inlet and outlet zone of the drier was found to be turbulent while the flow through the cobbed maize (porous) was laminar and characterized by inertial and viscous loss coefficients in the flow direction.

The cobbed maize is impermeable in other directions which were modified using loss coefficients, with its values three orders of magnitude higher than in X direction.

Modifications and formulation of the Navier – stoke equation reduces to their classical form which includes the additional resistance terms induced by the porous region.

3.7.1. Meshing and Boundary Conditions.

The computational mesh was generated using ANSYS Workbench with a certain number of elements and nodes. The numerical solutions of the involved equations in the ANSYS Fluent use specific boundary conditions. The boundary conditions were defined at different parts of the geometry.

The boundary conditions to be used in the calculations were determined considering the measurement from the actual industrial drier.

Table 3-1: Mesh parameters

Mesh statistics	
Number of Nodes	260
Number of elements	204

The parameters and physical properties of variables are very important during the analysis of the drying system.

The setup of the boundary conditions in the geometry was as described:

The inlet air velocity of the drier was set as 1m/s, 5m/s and 10m/s with the turbulent intensity being 5%. The variance helps in finding the effects of increasing air velocity on its profile in the drier. The direction of flow was normal to the inlet and inlet air temperature was assumed to be 370K.

The gauge pressure at the outlet of the drier was set as 0 Pa while the flow regime at the outlet was assumed as subsonic. At the wall of the drier, no slip and smooth wall boundary conditions were used because the velocity at the walls was assumed to be zero.

The turbulent boundary quantities were set to use the default ANSYS Fluent conditions.

Table 3-2: Properties of fluid used in CFD

Physical Parameters	**Notes**
Fluid	Air
Density of air(kg/m^3)	1.225
Specific Heat Capacity	6.96
Thermal conductivity(mW/mK)	24.35
Velocity Magnitude (Inlet)	1M/s, 5M/s and 10M/s
Temperature (Inlet)	370K
Porous Material	Cobbed Maize

Table 3-3 cobbed maize bed conditions

Physical Parameters	
Packed Bed	Cobbed maize
Average particle size	0.56
Bulk density(kg/m3)	282.38
Porosity	67.93
Sphericity of Particle	0.66

The simulation was done in two dimensions in order to simplify the drier and give an actual analysis of the air velocity and temperature profiles. This is also due to the inlet being in different plane of the geometry.

The simulation of the drier was done in two folds, first not considering the drying material and secondly with the drying maize as the porous material.

The simulation was done in two dimensions to give detailed air flow in the batch drier, the temperature and velocity profiles are represented in the 2D due to their position the same plane the simulation of drying was done considering the cobbed maize as a porous material.

3.8. Analysis Of Data

The data from the experiment were analyzed using the Microsoft Excel where the regression analysis was done to ascertain the suitability of known agricultural products drying curves to the experimental data. Fitting of experimental data was done.

The model solutions in terms of contours streamline and vector plots inside the drying chamber was seen using CFD ANSYS POST. The convergences of variables in the drying system were considered in the residuals.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

The results are presented and discussed in this section. The behavior of temperature and effect of relative humidity will be analyzed. The simulation results from Ansys Fluent software version R1 2019 will be looked into to know the effect of air velocity, pressure and temperature in drying of cobbed maize in a batch drier. The simulation was done in two folds one without load and the other with load as porous media. Heat transfer coefficient and mass flow rate for the experimental and simulation were compared to ascertain their suitability in solving drying problems. The outcome of mathematical modeling shows that Midili is the appropriate description of drying of cobbed maize in the batch drier.

4.2 Effects of Drying Parameters on the Drying Rate of Cobbed Maize in Batch Drier

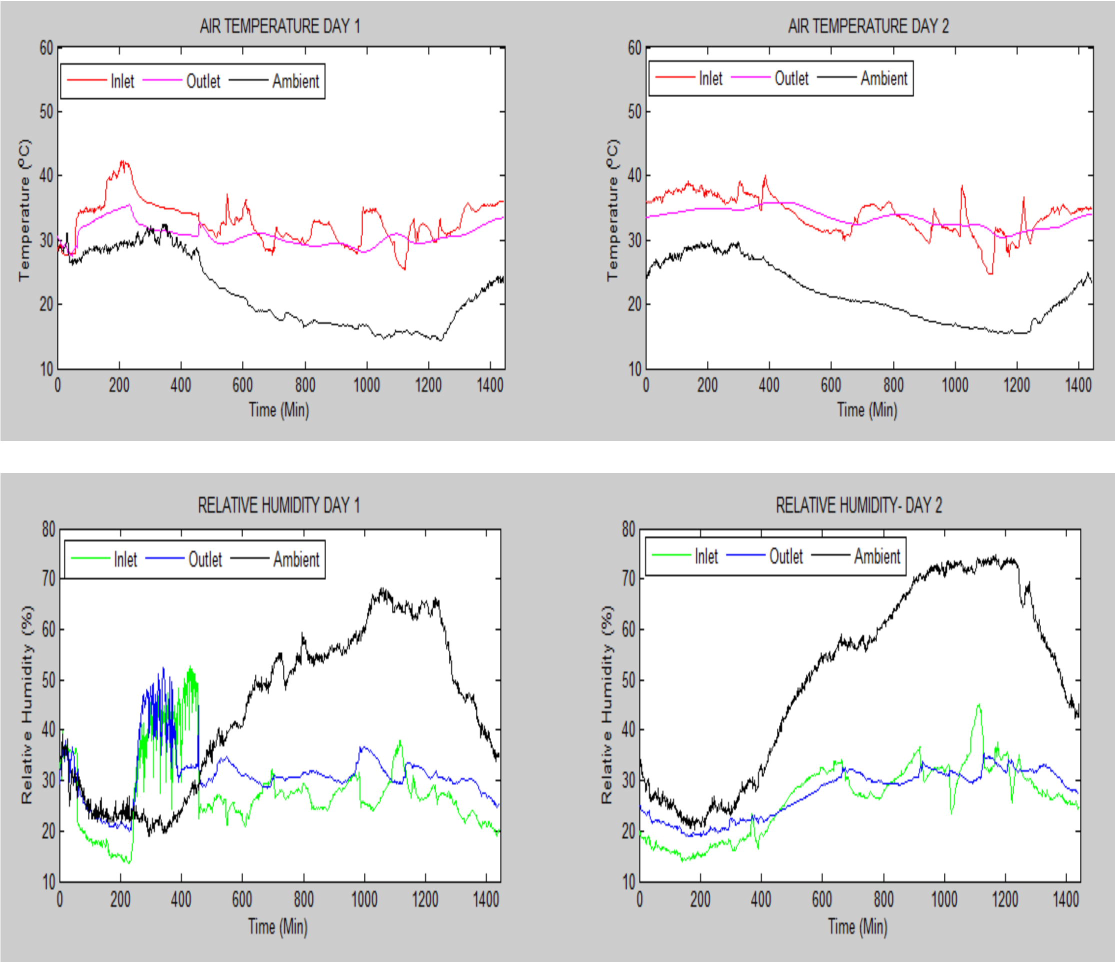

Figure 4-1: Behavior of air temperature and Relative Humidity at Inlet, outlet and ambient condition

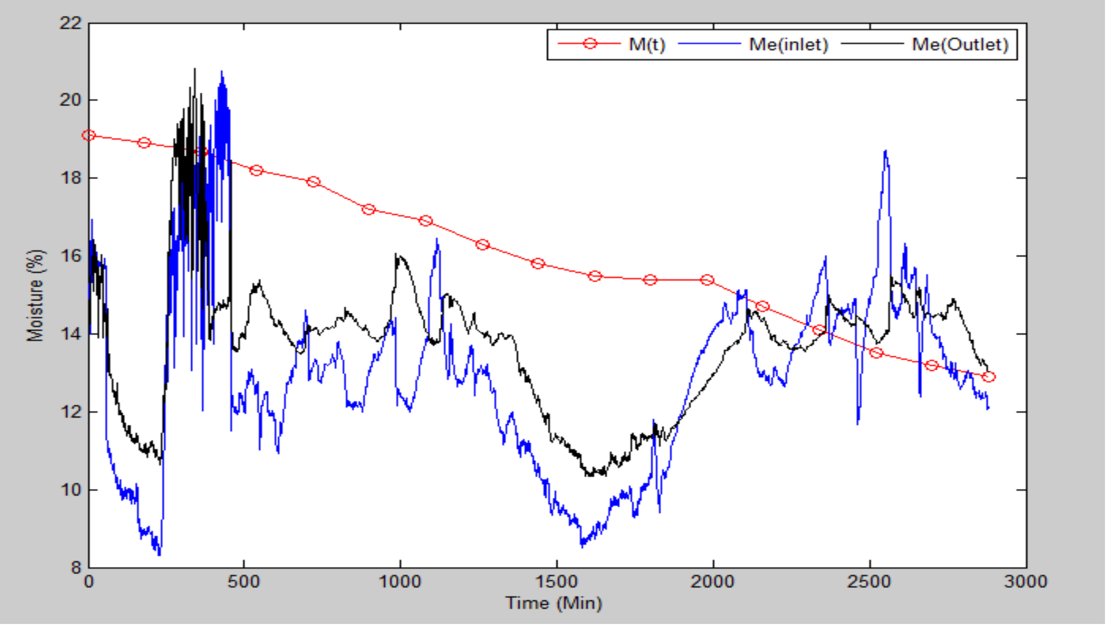

Figure 4-2: Moisture Loss by Cobbed Maize in the Drier

The figures above show that the temperatures and relative humidity at different points of the drier. When the relative humidity of inlet air is low, the temperature is at its peak and while the relative humidity is high the air temperature of inlet air is low. This shows that Relative Humidity has a significant effect on the drying kinetics of cobbed maize. This describes the water activity during drying meaning that the higher the relative humidity, the longer the period of drying. According to Tadao Inazo (December 2002), the effect of relative humidity on the apparent moisture removal has been found to be smaller than the effect of temperature however it cannot be neglected.

4.2 Simulation Results

Table 4-1: Mesh Data

	Maximum Face angle(degrees)	Minimum face angle(degrees)	Edge Length Ratio	Connectivity Number	Element Volume Ratio
Min	90	52.809	1.00992	1	1
Max	133.645	90	1.84818	5	1.9187

Table 4-2: Mesh Information

Number of Nodes	Number of Elements	Tetrahedral	Wedges	Pyramids	Hexahedra	Polyhedra
520	204	0	0	0	204	0

4.3: Air Flow Through Empty Batch Drier

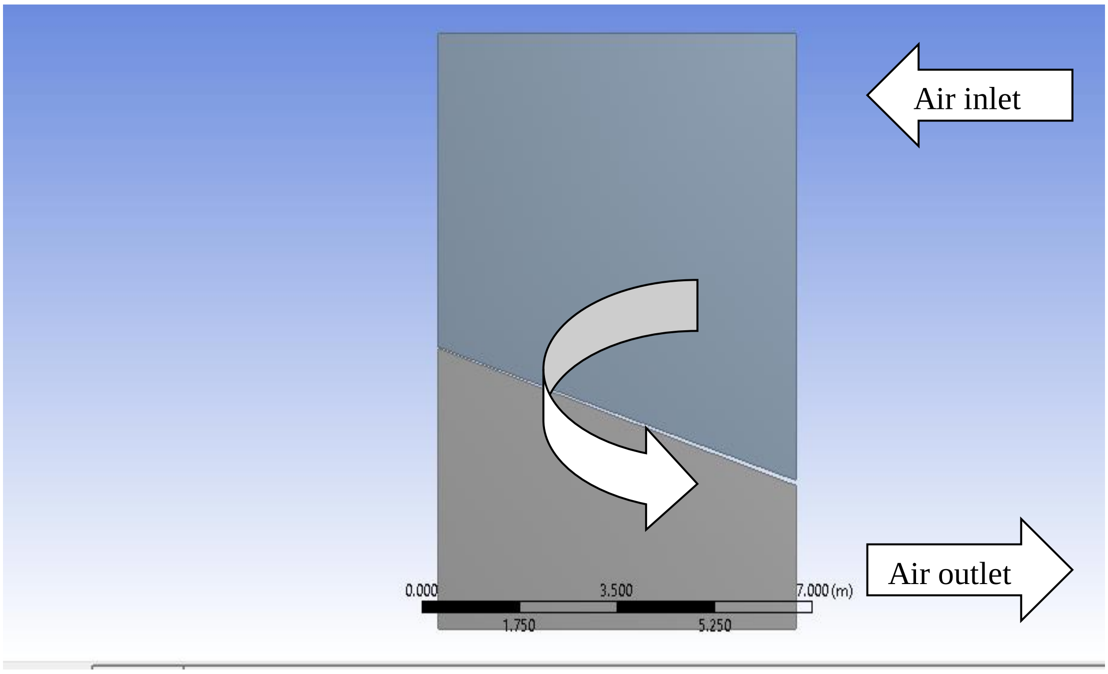

Figure 4-1: Geometry of drying system when there is no Maize

The simulation was done in two folds one without load and the other with load as porous media. The figure 4.4 shows the geometry of drying system where there is no load.

The air flows through the vacuum with no resistance since there are no cobbed maize to slow air movement.

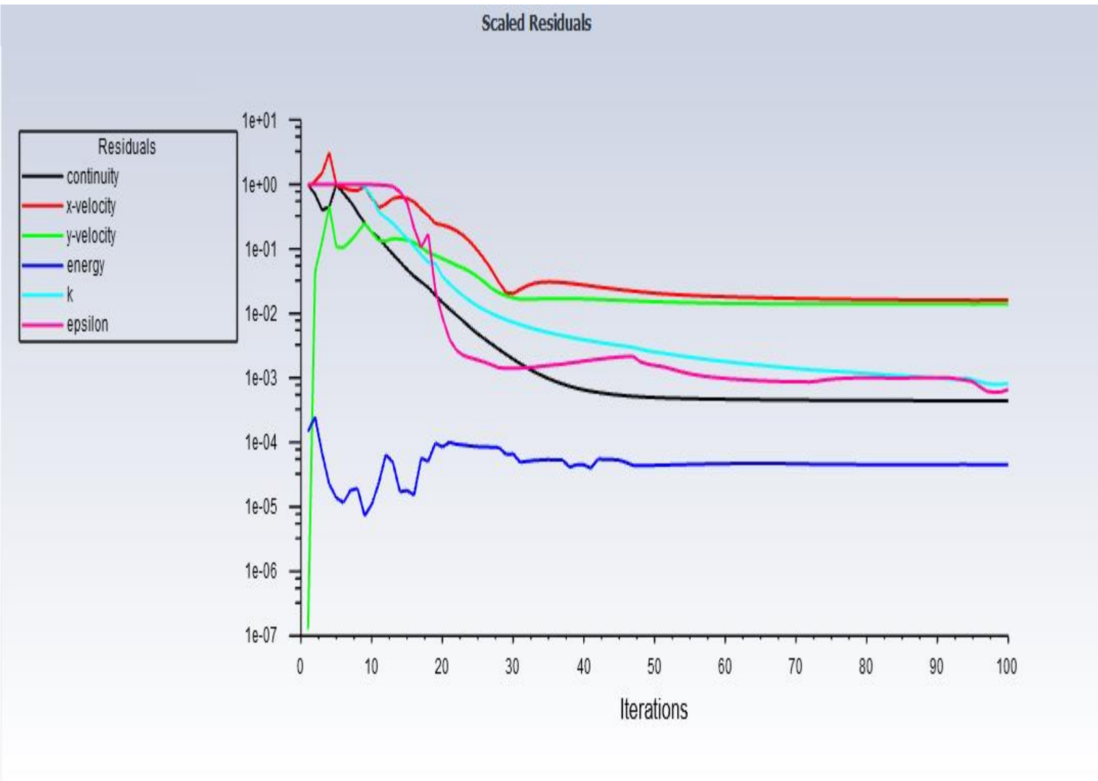

Figure 4-2: Residuals graph when there is no product

Figure 4.4 shows the residuals when the simulation was done when the bin is empty. It shows that there was convergence at the scale of 10^{-5}. This shows that meshing of the geometry was appropriate and the iteration done on the simulation gives a clear representation of the performance of the variables.

Computational Fluid Dynamics (CFD) methods involve iterative processes which achieves certain simulation solutions. The residuals reach a certain state and level to achieve the convergence. The convergence criterion is explained by the error which is accepted in the given values.

4.4 Air Flow Through A Loaded Batch Drier

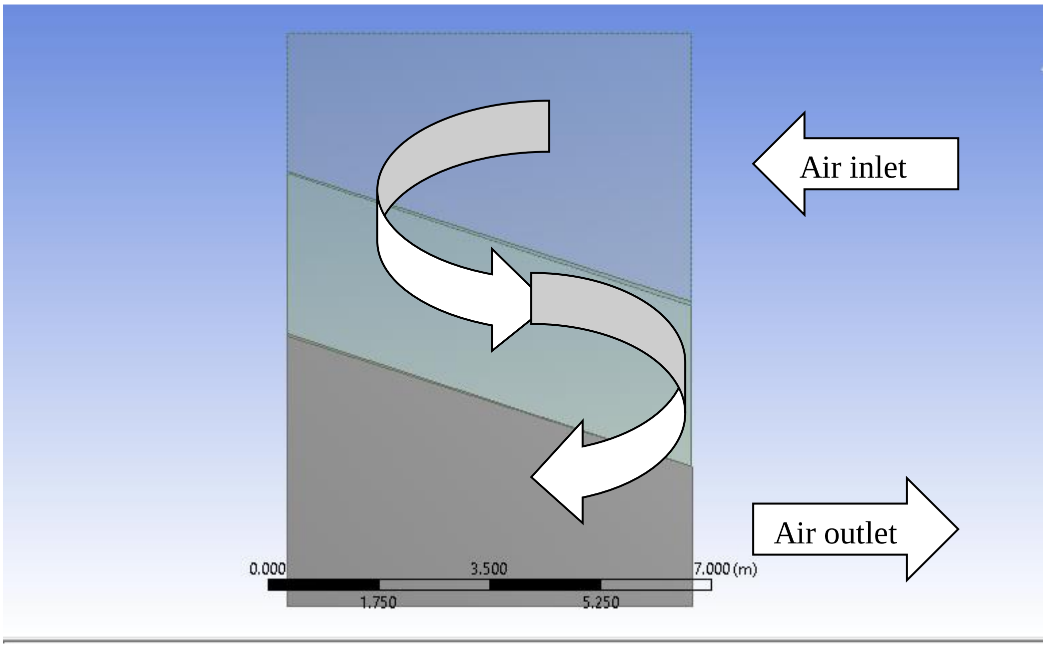

Figure 4-1: Geometry of drying system when there is load.

The figure 4.5 shows the geometry of the drying system with loaded cobbed maize. The drying air with elevated temperatures is passed through the cobbed maize packed in a bed made of coffee mesh. The packed cobbed maize is assumed to be a porous material for ease of simulation.

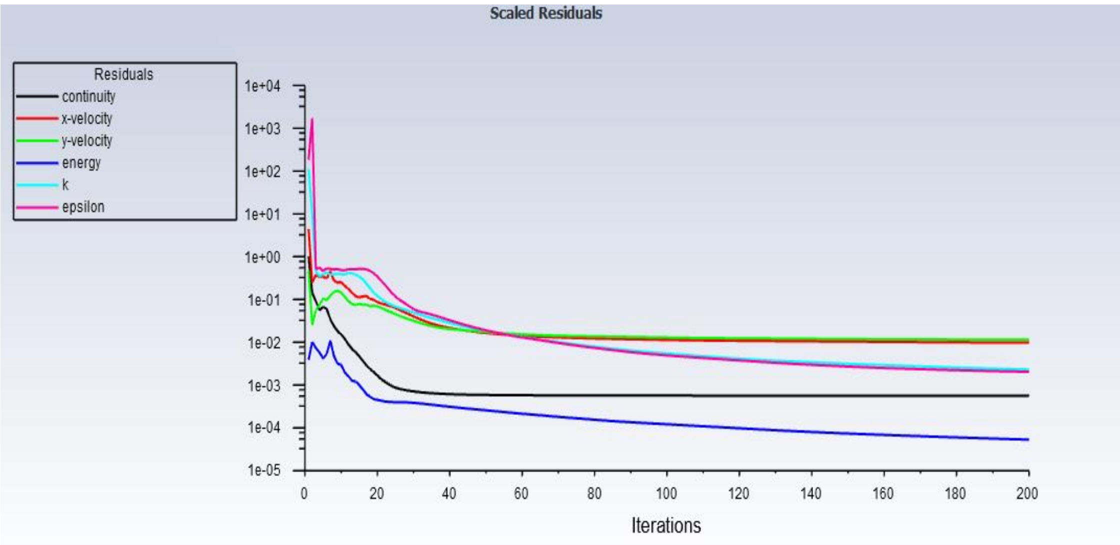

Figure 4-2: Residuals at 1m/s

Figure 4-6 gives the behavior of the residuals at 1m/s. This shows that there is convergence at

10^{-4} proving that the geometry was successfully meshed hence will give the right simulation solution.

Computational fluid dynamic (CFD) simulation has the objective of determining the values of engineering quantities with respect to iteration and defines iterative convergence when these quantities converge. Different quantities reach convergence at different periods.

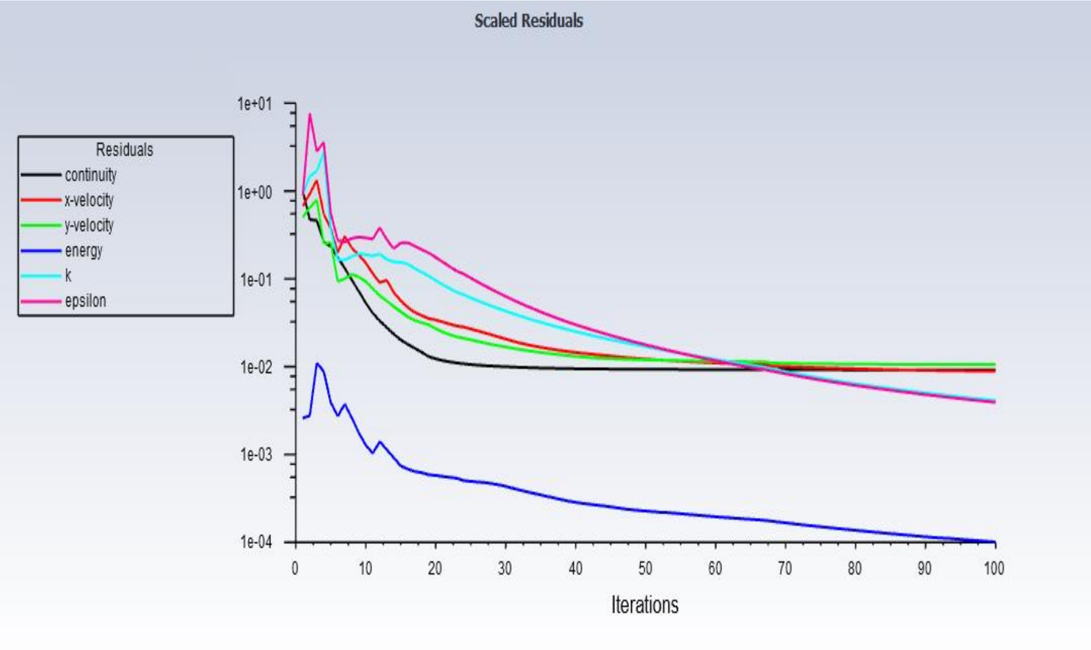

Figure 4-3: Residuals at 5m/s.

At the air velocity at 5 m/s, the iterative convergence is at 1e-4 which shows that the residuals are loosely convergent and numerically accurate thus giving the right solution.

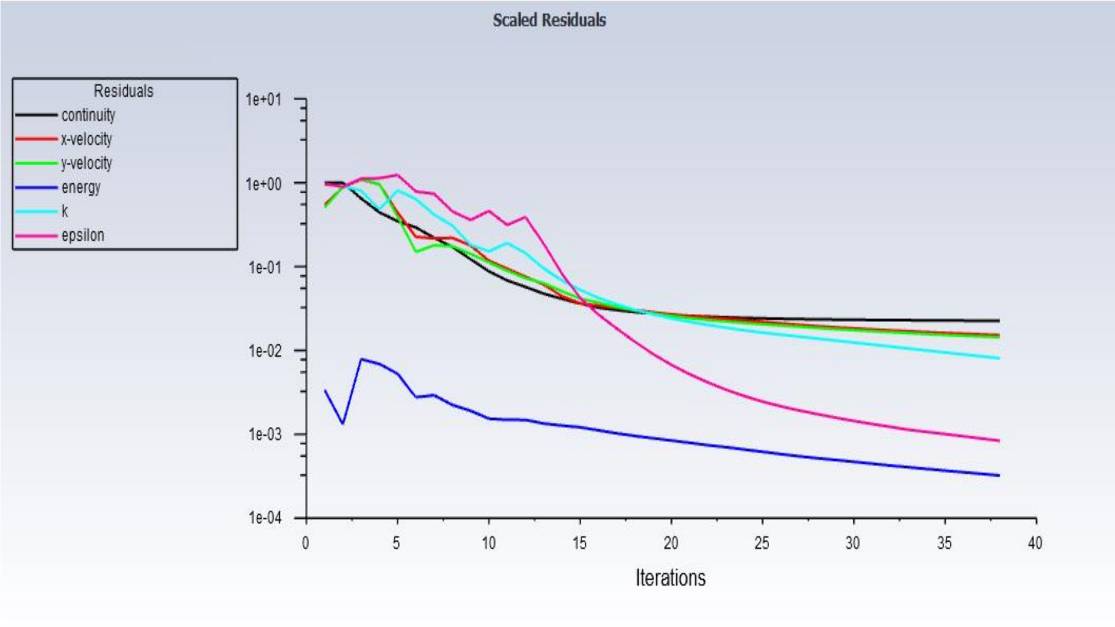

Figure 4-4: Residuals of 10m/s

The residuals of air flow at 10m/s is shown in figure 4-8.The figure shows that there is convergence at 1e-04 ensuring that meshing is appropriate and the solution can be found.

4.5 Velocity Contours At 1M/S, 5M/S And 10M/S

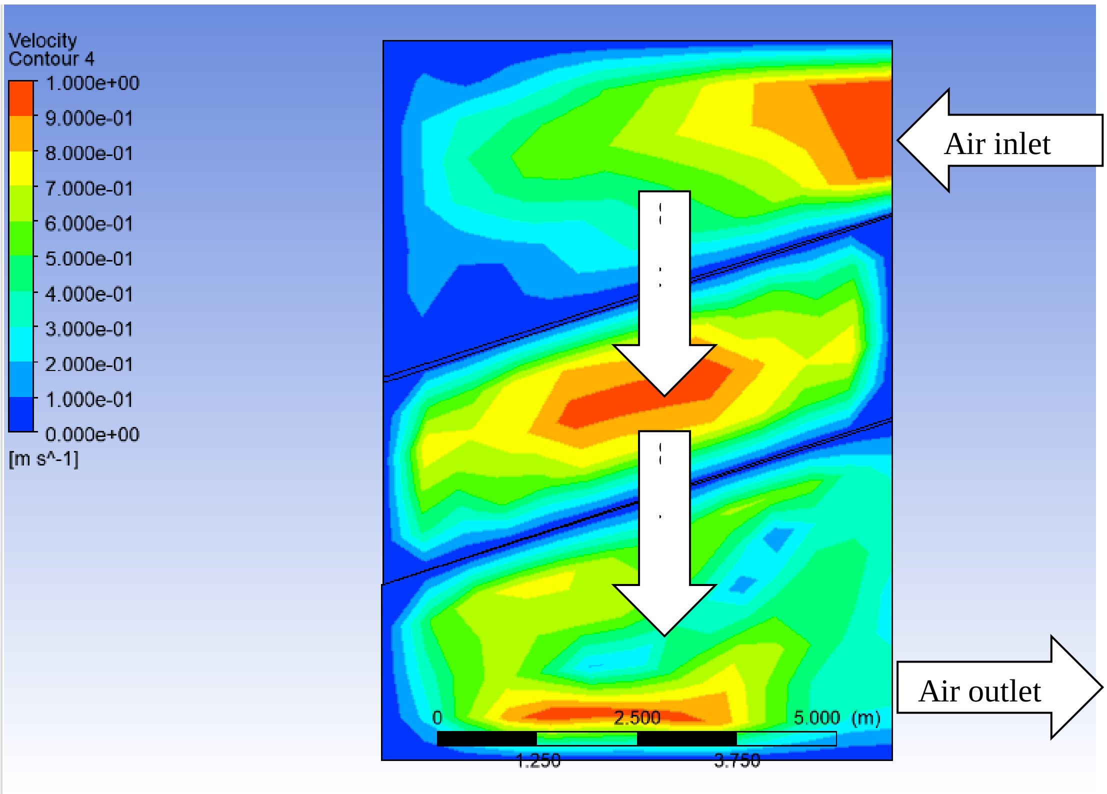

Figure 4-1: Velocity contour at 1m/s

Figure 4-9 shows how air velocity behaves inside the drying bin with cobbed maize. It is evident that there are regions inside the drier which air velocity is low. It's evident that inside the bin there is variance in rate of drying hence when one is designing a drying system, the velocity of air inside the bin must be defined and considered. This will ensure that there is uniformity in the drying rates and moisture content reduction of the cobbed maize.

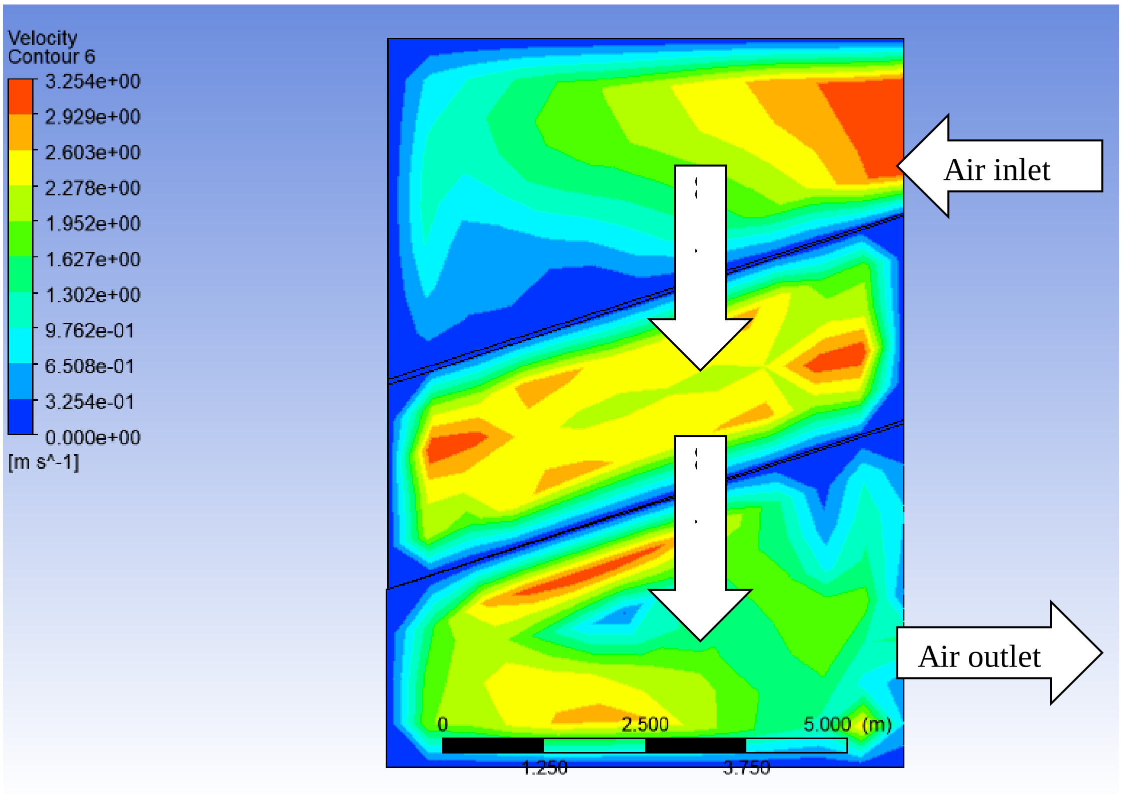

Figure 4-2: Velocity contour at 5m/s

The velocity profile inside the bin exhibited same behavior despite change in the magnitude of air velocities; the rate of drying is affected by change in the rate of air flow. During drying, the air flow profile is affected by how the batch drier is designed.

From the Figure 4-10, the velocity contour of air flow at various magnitudes inside the drying bin is demonstrated. The air distribution shows that at inlet zone, air flow velocity is high while there is a decrease as air moves towards the wall. At the outlet zone, air flow velocity is at lowest in the walls however there are other regions which the velocity of air flow is high.

The velocity distribution of air flow at inlet is at the range of 1m/ and reduces as it moves towards the walls making lowest at the walls. The flow of air inside the product, the air velocity is higher at the middle of the cobbed maize and very slow around its boundaries. In the outlet zone the air flow is low at the walls but some places there is higher. In comparison with inlet and product zone, the air velocity tends to reduce. From all the velocity contours for 5m/s and 10m/s there is no difference in the distribution air however its magnitude tends to vary with change in velocity of air flow.

4.6 Pressure Contours at 1M/S, 5M/S AND 10M/S

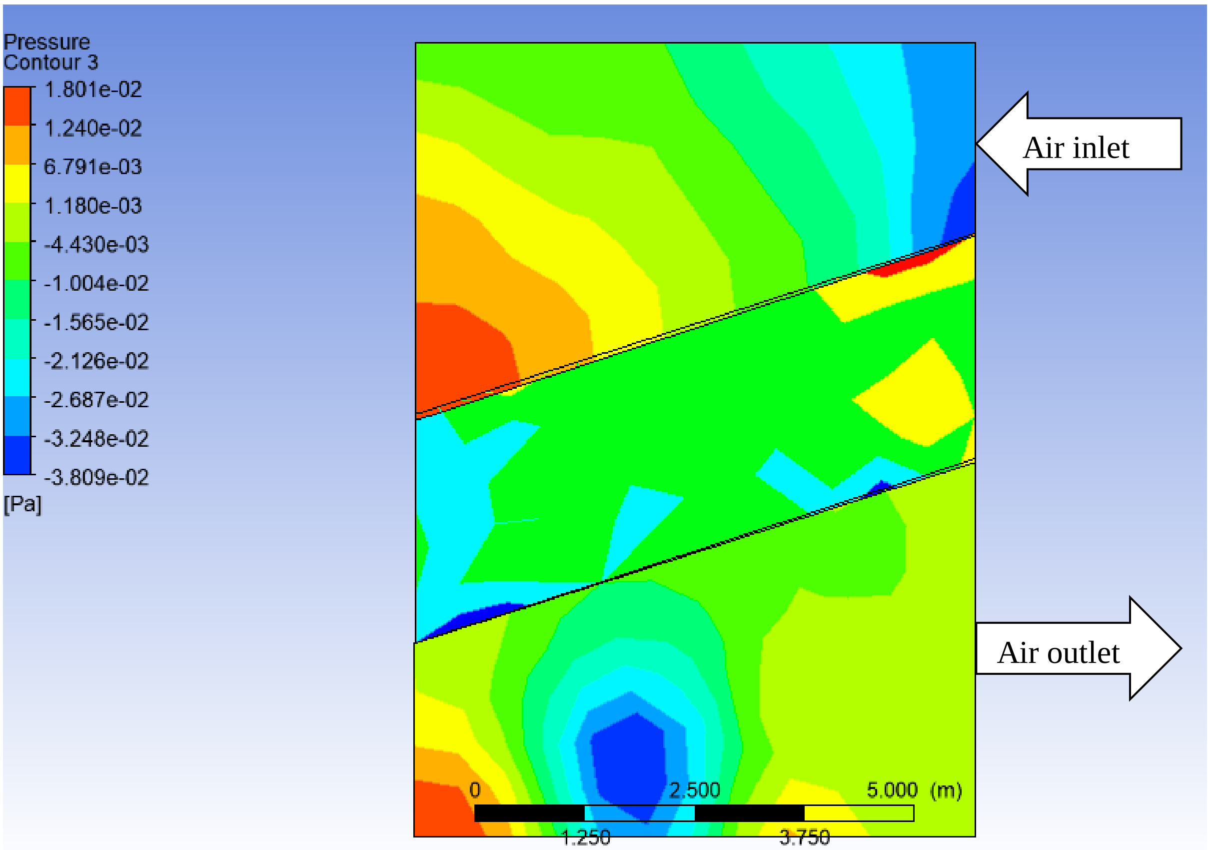

Figure 4-1: Pressure contour at 1m/s

Figure 4-11 represents the pressure of air inside the bin filled with cobbed maize. The contours of the pressure in the bin depend on the region and geometry of the drier.

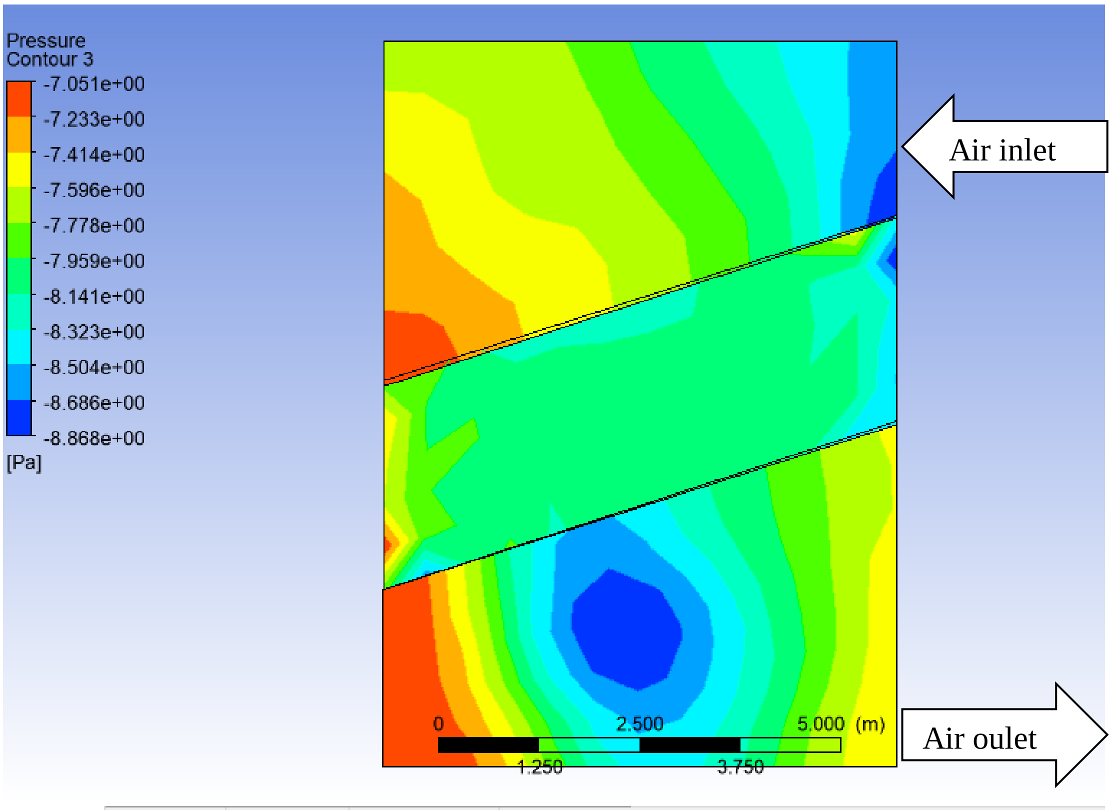

Figure 4-2: Pressure contour at 5m/s

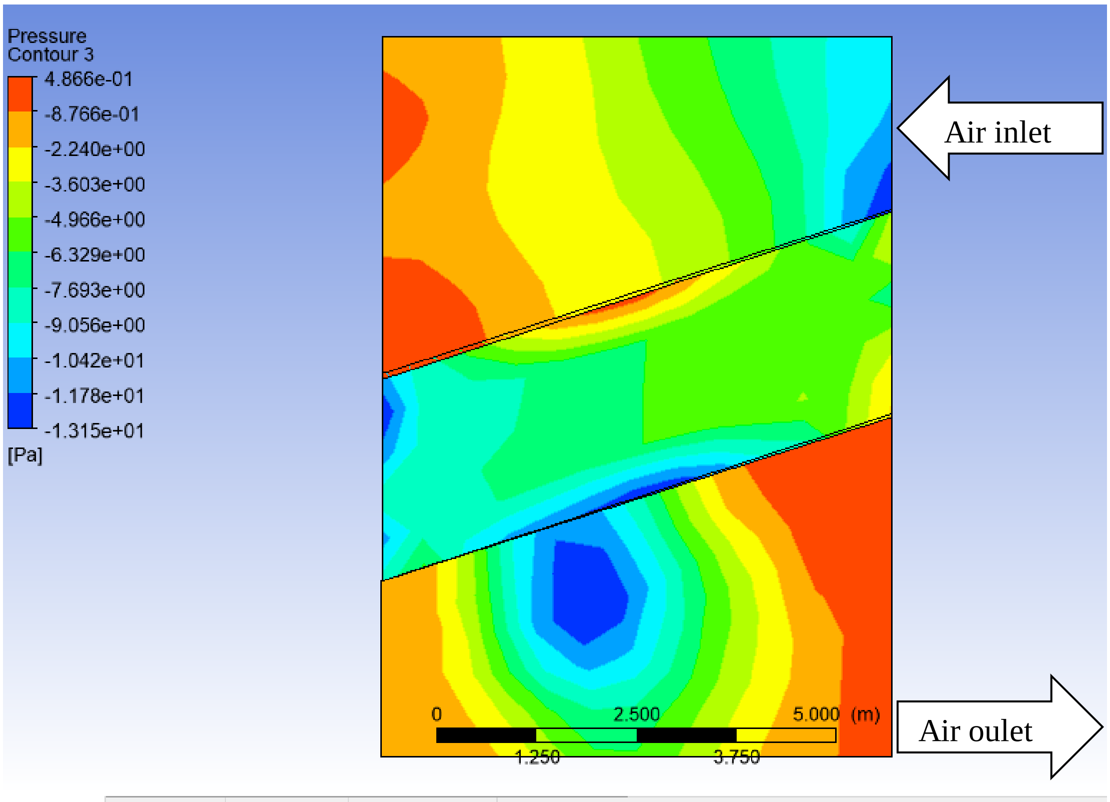

Figure 4-3: Pressure profile at 10m/s

From the pressure contours on figures 4.11, 4.12, and 4.13 it is evident that change in air flow velocity does not affect the pressure profile in the drier however, the geometry of the drier has an impact on the movement of air and consequently affecting the rate of drying.

Pressure inside the drier the monitored air velocities are in the same range only that there is change in the magnitude.

From the figures it is evident that at walls, the pressure magnitude is higher due to resistance of the wall.

4.7 Streamline of Air Flow at 1M/S, 5M/S AND 10M/S

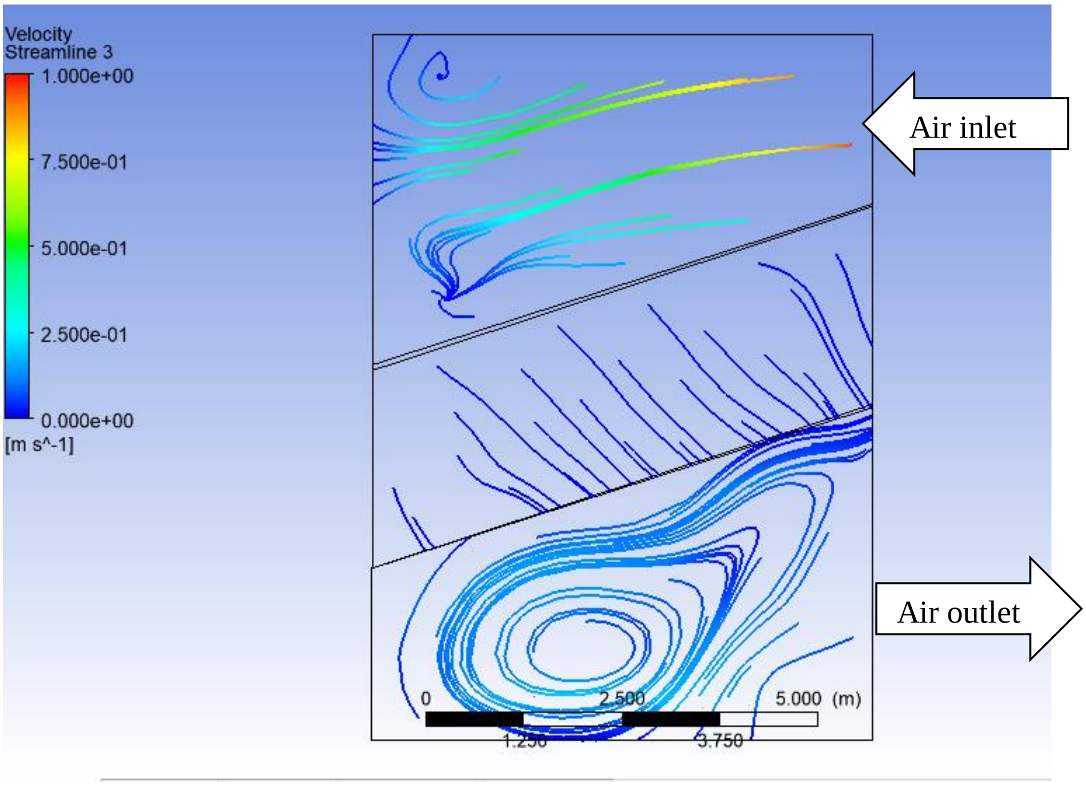

Figure 4-1: Streamline of air flow at 1m/s

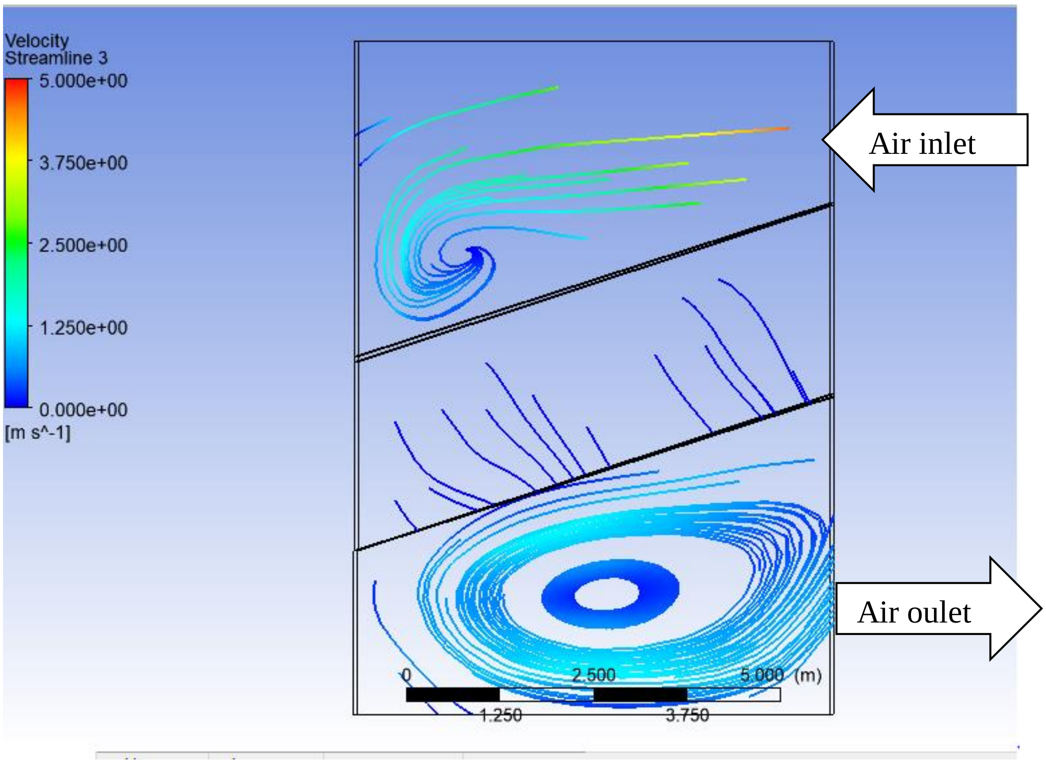

Figure 4-2: Streamline of air velocity at 5m/s

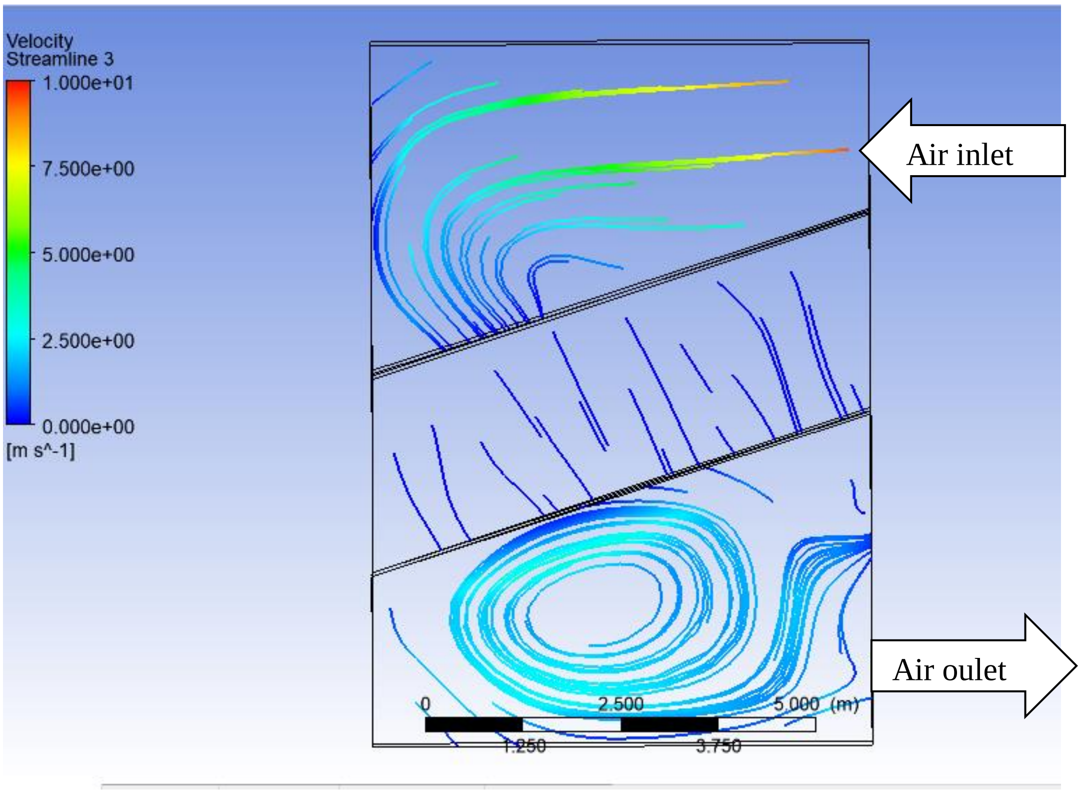

Figure 4-3: Velocity Streamline

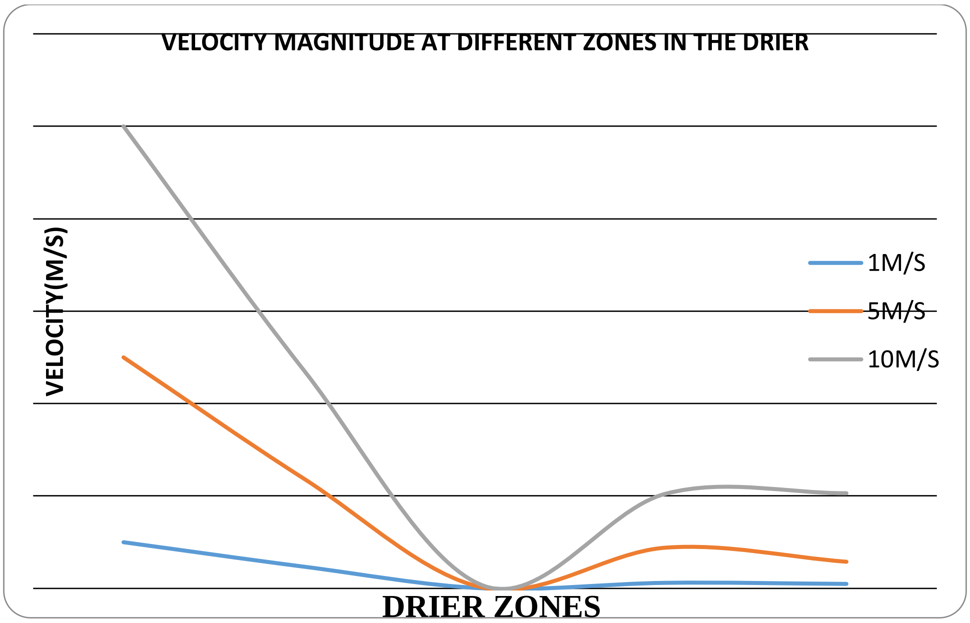

Figure 4-4: Velocity Magnitude at the drier

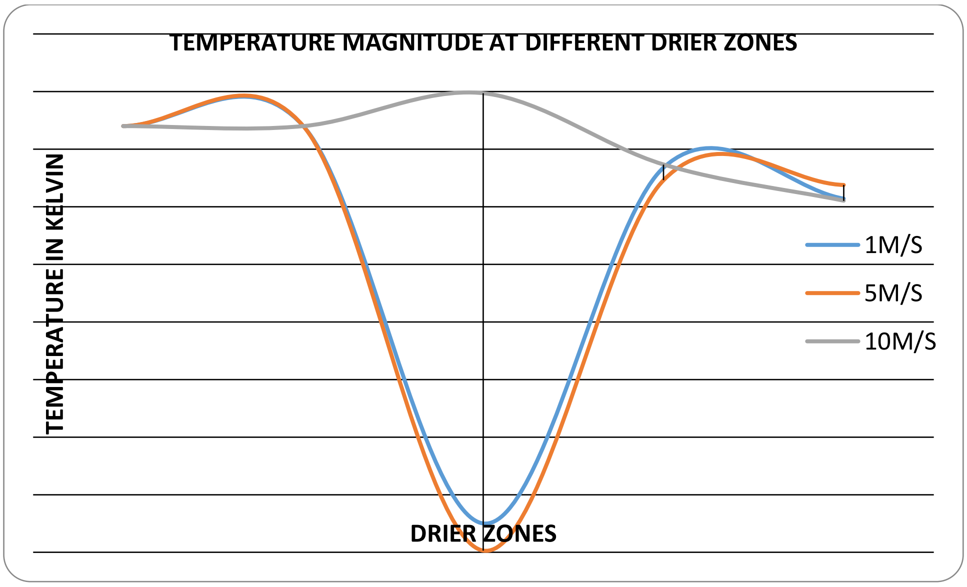

Figure 4-5: Analysis of ANSYs Fluent Results

2D simulation saves time and helps in quick evaluation of a given model. The main result was the value of heat transfer coefficient α and mass flow rate β. From the CFD Post the results are as shown in table 4-3.

Table 4-1: CFD Post Process results

Description	**Value**
Heat Transfer coefficient	1.28W/m^2K
Mass flow Rate	26.27kg/S

4.8: Heat and Mass Transfer Analogy

It has been noted there exist an analogy between mass and heat transfer coefficients.

The experimental and CFD results were compared to ascertain their conformity and the performance at the air velocity was set at 2 m/s

Table 4.4 Showing Experimental, CFD and Analytical values of heat and mass transfer coefficient at 2 m/s

Table 4-1: CFD and Analytical values of heat and mass transfer coefficient

Experimental	**CFD Model**	**Analytical**
	α=26.27W/M^{2}K	α=22.20W/M^{2}K
β=1.83m/s	β=1.28m/s	β=2.4m/s

From the results, it is evident that the values gotten from experimental, CFD and analytical relationship shows that they are in the same order.

It is therefore worth to note that there is concurrence of the results hence all the methods can be used. However, CFD presents the most effective and time saving method**.**

4.9: Mathematical Modeling Of Cobbed Maize Drying

4.9.1. Moisture Loss in Cobbed Maize

Drying is a complex process which involves the transfer of heat and mass inside the cobbed maize and its surrounding. The movement of moisture from the cob towards the surface of the cobbed maize is dependent on the structure and properties of the cobbed maize, drying temperature and the moisture of the cobbed maize. The amount of the moisture in the surrounding atmosphere contributes to the rate of heat and mass transfer.

Simulating the drying process of cobbed maize in the batch drier provides accurate information to evaluate the energy and time phenomenon in the drier. Simulation assists to faster know the effects of several parameters in the drier hence saving in time and cost.

There are several models which have been proposed in the literature which are either empirical equation or theoretical. The theoretical models are got through the evaluation of diffusion equations and the solution of mass and heat transfer in the batch drier. The semi theoretical models are found from the Newton's cooling law which explains the rate of drying to the variance in the moisture content at a given time and its equilibrium moisture content (EMC) (McDonald, [2007]).

Empirical models use exclusively data from the experiments and gives out the mathematical equations that are used to fit the data. (Sharaf-Elden Y I, 1980)

The drying data obtained from the experiments is curve fitted to the proposed mathematical models as per the literature established.

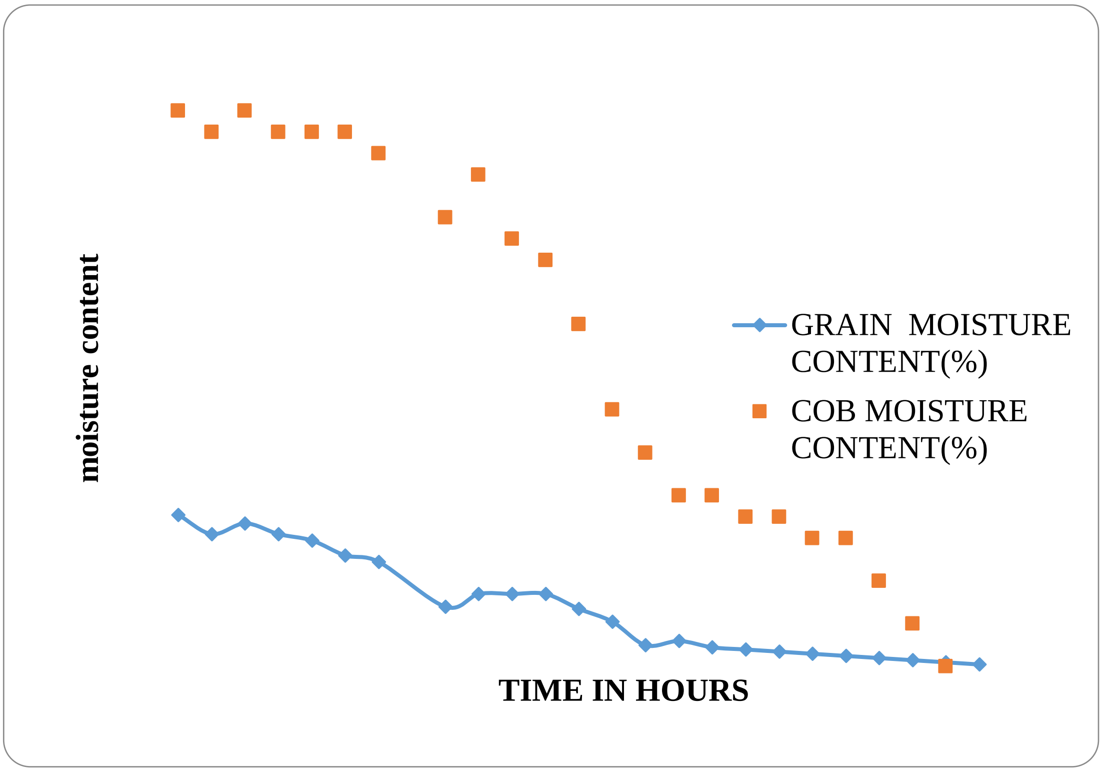

Figure 4-1: Moisture Loss Due To Drying Vs. The Drying Time at Inlet Temperature and Air Flow Rate

The drying rate falls at constant rate in both the grain and cobs while it continues falling till at some point the drying rate reduces to the required point of 13%.

To find the best mathematical model which can fit the drying process of drying cobbed maize in a batch drier, the known models of agricultural products which have been explained in the literature is used to fit the curve.

The data obtained from the experiment done was converted to dimensionless moisture content according to the equation:

$MR = \frac{M - Me}{Mo - Me}$ ....Equation 4-1

Where M is the moisture content of the cobbed maize at a given time, M_e is the equilibrium moisture content of the cobbed maize and M_o is the initial moisture content of the cobbed maize.

The description of the drying kinetics of the cobbed maize, there are several mathematical models which have been described in the literature describing the behavior of several parameters in the drying of agricultural products. The accuracy and consistency of the models to the experimental data was measured using the coefficient of reliability (R^2) and the chi-square (χ^2) of the data obtained. It should be noted that if the value of R^2 is high and χ^2 is low then the experimental data and the mathematical model is in agreement. The objective function is defined by the chi-square obtained through the fit of the analytical solution to the experiment

The models have been shown in table 4-5

Table 4-1: Mathematical models to obtain the drying curves of agricultural products

Model Name	Model Equation
Page	MR=$\exp(-kt^n)$
Diffusion approach	MR=$\exp(-kt) + (1-a)\exp(-kbt)$
Two term exponential	MR=a $\exp(-kt) + (1-a)\exp(-kbt)$
Vema	MR=aexp(-kt)+(1-a)exp(-gt)
Newton	MR=exp(-kt)
Midili	MR=aexp(-kt^n)+bt
Logarithmic	MR=aexp(-kt)+b
Henderson and Pabis	MR =aexp(-kt)
Two-term model	MR=aexp(-kt)+bexp(-gt)
Modified Henderson and Pabis	MR=aexp(-kt)+bexp(-gt)+cexp(-ht)

4.9.2. Equilibrium Moisture Content

Equilibrium moisture content is the moisture level where the cobbed maize neither gains nor looses moisture since it is at equilibrium with the relative humidity and temperature of the surrounding environment.

As long is the fiber saturation point is not reached, the relative humidity and temperature of the atmosphere significantly affect the moisture content of cobbed maize.

The equilibrium moisture content is dynamic in nature because the ambient conditions such as relative humidity and temperature are constantly changing.

For each value of relative humidity for a given temperature, there is corresponding EMC percentage; therefore EMC can be plotted as a function of relative humidity for a known temperature.

For estimation of a true target of EMC at any value of relative humidity and temperature, the following equation is used;

$EMC = [-\ln(1 - RH) / 4.5 \times 10^{-5} (T + 460)]^{0.63}$ --------------------------------Equation 4-2

4.9.3. Calculating Mass Transfer Rate K_c

The understanding of the kinetics of drying is required if one need to analyze the drying of materials in large scale. The physical and thermal properties of the material to be dried and the heat and mass transfer within the material need to be studied. In the batch drying of the cobbed maize, these parameters are very essential in the design of the drier. The diffusion coefficient, mass transfer coefficient and the activation energy of cobbed maize will be determined from the experimental data.

4.9.4. Diffusion coefficient

The movement of fluid from higher concentration to an area of low concentration is defined as mass diffusion.

The equation defining diffusion of property momentum, heat or mass in the given direction is:

$\boldsymbol{\psi}_{\boldsymbol{z}}=-\delta\frac{\boldsymbol{d}\Gamma}{\boldsymbol{dz}}$.. Equation 4-3

$\frac{d\Gamma}{dz}$ -is the driving force (concentration gradient in the mass transfer, temperature difference) per unit area.

The Flick's law of diffusion states that the flux goes from the region of high concentration to the region of low concentration with the magnitude which is proportion to the concentration gradient and it is given by the equation 4.2.

The flux (diffusion) movements from material A to B in the direction of z is given by,

$J_{\boldsymbol{AZ}}=-\boldsymbol{D}_{\boldsymbol{AB}}\frac{\boldsymbol{dcA}}{\boldsymbol{dz}}$...Equation 4-4

The calculation of the diffusion coefficient is calculated using the equation as shown below:

$\mathrm{MR}=\frac{\boldsymbol{M}}{\boldsymbol{M}}=\frac{\mathbf{8}}{\boldsymbol{\pi}^{\mathbf{2}}}\sum_{\boldsymbol{qn}=\mathbf{0}}^{\infty}\frac{\mathbf{1}}{(\mathbf{2n-1})}\mathbf{exp}(-\frac{(\mathbf{2n-1})^{\mathbf{2}}\boldsymbol{\pi}^{\mathbf{2}}\mathbf{D}_{\mathbf{AB}}\mathbf{t}}{\mathbf{4L}^{\mathbf{2}}})$.................................. Equation 4-5

In this equation the MR is the moisture ratio defined as the ratio of the moisture at a given time during drying of cobbed maize to the initial moisture.

Moisture is given by the percentage of weight of water to the weight of dried cobbed maize.

Only the first term is used for long drying of agricultural materials. Therefore, the above equation becomes:

$MR=\frac{8}{\pi^2}\exp(\frac{\pi^2 D_{AB} t}{4L^2})$.. Equation 4-6

Taking natural logarithm (Ln) of both sides of above equation gives:

$Ln(MR) = Ln\left(\frac{8}{\pi^2}\right) + \frac{\pi^2 D_{AB} t}{4L^2}$--Equation 4-7

The above equation is analogous to a linear equation of the form a+bt which can be plotted on the graph a against t where b is the slope of the graph.

Therefore plotting Ln (MR) vs. time will give the slope of $\frac{\pi^2 D_{AB}}{4L^2}$.

Hence

$\boldsymbol{D_{AB} = \frac{4L^2}{\pi^2} b}$-- Equation 4-8

The equation above was used with the experiments data obtained to calculate the diffusion coefficient of the batch drying cobbed maize.

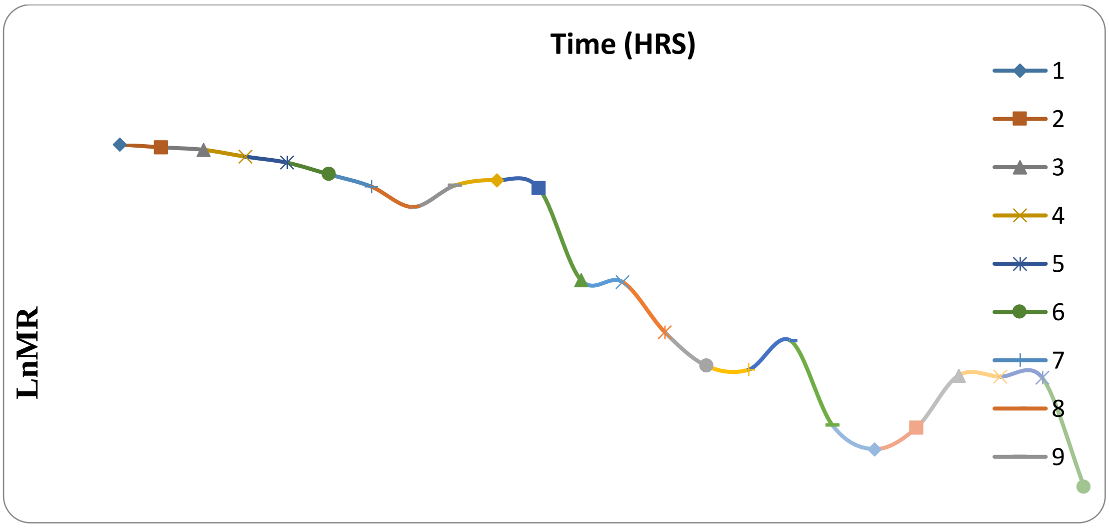

Figure 4-2: Plot of Ln MR vs. Time in Hours

From the Figure 4-20, it can be observed that the plot is not as linear meaning that the drying is irregular but considering the first 8 hours it is seen that the line curve is linear showing that the initial stages of drying; the moisture drops in a constant rate.

As found in the study by (Dejahang, 2015), when the surface moisture of a material is high enough to maintain drying at constant rate there is high coefficient of diffusion. As the water in the surface of the cobbed maize is cleared, the moisture inside the grain and the cob tends to move outside and it will try to overcome the resistance moving from the capillaries and inside pores towards outside. The resistance will lead to reduction in the moisture content removal rate hence reducing the diffusion coefficient.

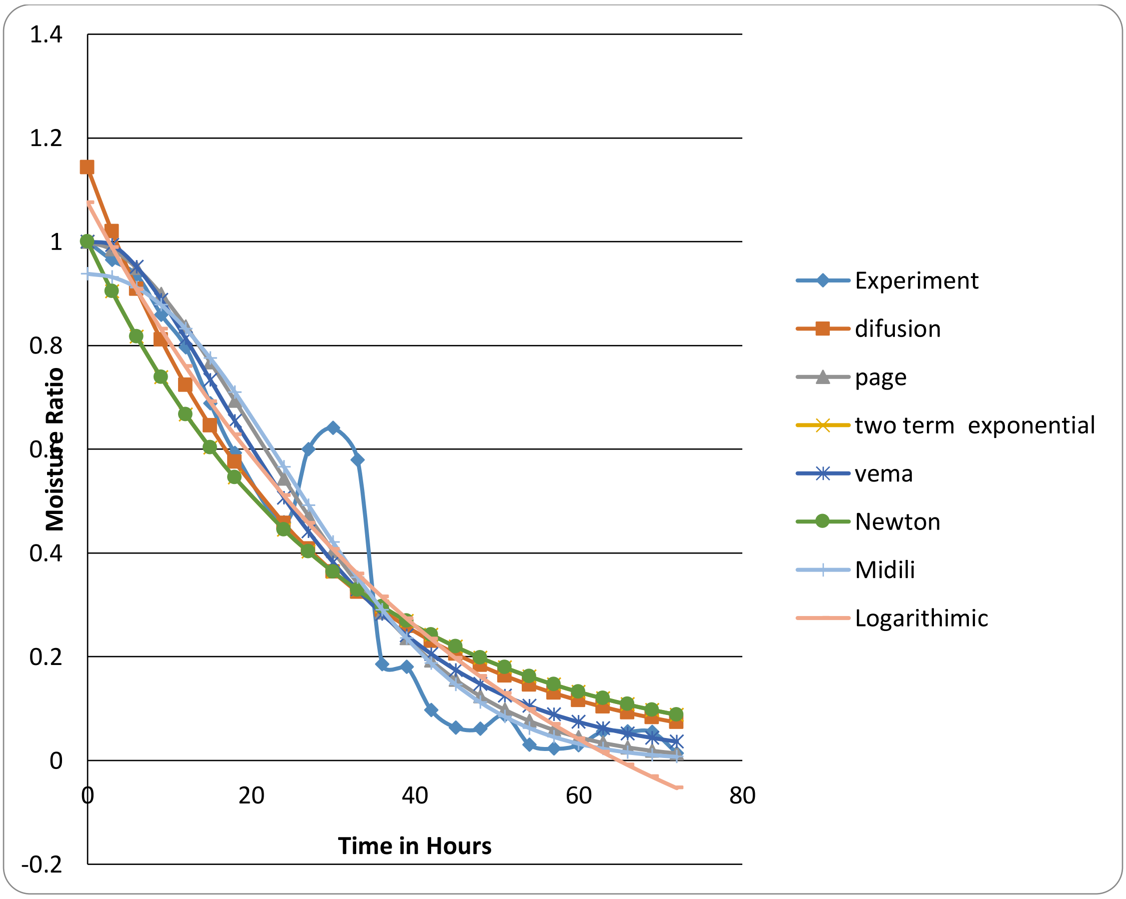

Figure 4-3: A graph showing Mathematical models to obtain the drying curves of agricultural products

4.10 Conclusion

The accuracy of a given model is determined using the coefficient of reliability (R^2) and RMSE. It should be noted when the value of R^2 is high and the value of RMSE is low, it shows that there is an agreement between the mathematical model and the experimental data.

The table shows the values of $\chi 2$, R^2 and RMSE for the models considered in order to identify the one which best fit the drying curve for the cobbed maize in the convective batch dryer. It was found that based on the values of R^2 (the bigger the value the better) the one for Midili was the best and has been confirmed by the values of RMSE which are low (the smaller the better).

Table 4-1: Table shows the values of $\chi 2$, R^2 and RMSE for the models.

Model name	Resulting coefficient and constants	R^2	RMSE
Page	k=0.002162 n=1.7755	0.939	0.090766
Diffusion approach	a=0.8576 b=1.0000 k=0.0337	0.889	0.11699
Two term exponential	a=0.8018 b=1.00012 k=0.033736	0.909	0.12719
Vema	a=-28.77 g=0.07 k=0.0337	0.927	0.096656
Newton	k=0.03376	0.909	0.12719
Midili	a=0.938 b=0.000 k=0.00069 n=2.073	0.946	0.012704
Logarithmic	a=1.475 b=-0.4 k=0.02	0.964	0.0153

CHAPTER FIVE

CONCLUSION

The experimental results show that temperature and the relative humidity have a significant effect on drying kinetics. The rate at which water is removed from the cobbed maize is affected the relative humidity of the drying air however its effects is relatively small than that of temperature.

Simulation was done in two folds, one without load and the other with the load. The plots of residuals of both scenarios have the convergence at the scale of 10^{-5} and 10^{-2} showing that meshing was appropriate for the investigation of the effects of variables in the drying systems.

The velocity magnitude was represented using the velocity contours. The velocity intensity at the walls is low was found to be contributing to slow drying at the corners of the drier. This lead to variance in the uniformity in the drying across the drier implying that the geometry of the drier impacts the drying kinetics hence need to be considered when on designing the drier.

The rate of air flow in the drier does not change its distribution however the rate of drying is affected.

The comparison of the results from the experiments and simulation shows that there are similarities hence they can work in alternate. The results are in the same order and it is worth noting that there is concurrence of the results hence all the methods can be used however CFD presents the most effective and time saving alternative.

The experimental results were fitted to models of agricultural products as discussed in literature. The one which best fitted the drying curve of cobbed maize is Midili which was confirmed by the values of R^2 and RMSE. Further research is recommended to assess the impact of moisture content, cob size and fines / shell out on batch drying kinetics.

REFERENCES

Akosman, C. (2004). Determination of drying characteristics and effective diffusivity for sugar cubes. *Chemical Engineering & Technology , 27* (11), 1222-1226.

Corrêa, P. C., Botelho, F. M., Oliveira, G. H., Goneli, A. L., Resende, O., & Campos, S. d. (2011). Mathematical modeling of the drying process of corn ears. *Acta Scientiarum. Agronomy* , 575-581.

Defraeye, T. (2014). Advanced computational modelling for drying processes - A review. *Applied Energy , 131*, 323-344.

Dejahang, T. (2015). *Low Temperature Fluidized Bed Coal Drying: Experiment, Analysis and Simulation.* University of Alberta: Department of Chemical and Materials Engineering.

Djiako, T., Edoun, M., Desmorieux, H., Kuitche, A., & Tawetsing, O. M. (2018). Numerical Simulation of Effect of Topology on the Airflow Characteristics inside an Indirect Solar Dryer. *American Journal of Energy Research* , 1-7.

Ekechukwu, O. (1999). Review of solar-energy drying systems I: an overview of drying principles and theory. *Energy Conversion and Management , 40* (6), 593-613.

Foerster, M., Woo, W., & Selomulya, C. (2016). Single Droplet Drying. *Reference Module in food Science* .

Giraldo-Zuniga, A. D., Arévalo-Pinedo, A., Rodrigues, R. M., Lima, C. S., & Feitosa, A. C. (2004). Drying Curves And Water Activity Evaluation For Sliced Jackfruit (Artocarpus Integrifólia). *14th International Drying Symposium* (pp. 1776-1783). Sao Paulo,Brazil.: Researchgate.

Kundu, P. K., Cohen, I. M., & Dowling, D. R. (2011). *Fluid mechanics* . Academic Press.

McDonald, M. (2007). Seed moisture and the equilibrium seed moisture content curve. *Seed technology , 29* (1), 7-18.

Mujumdar, A., & Zhonghua, W. (2008). Cost-Effective Innovation Aided by Mathematical Modeling Approach. *Drying Technology , 26* (1), 145-153.

Recktenwald, G. (2020). Introduction toTurbulence Modeling for CFD. *Mechanical and Materials Engineering Department Portland State University, Portland, Oregon* .

Saadani, R., Rahmoune, M., Sbai, K., & Dafir, D. (2014). Modeling Simultaneous Heat and Mass Transfer in Porous Media. *International Journal of Engineering Innovations and Research , 3*, 425-429.

Scheidegger, A. E. (1974.). *The physics of flow through porous media. 3rd edition.* Toronto: University of Toronto Press.

Sharaf-Eldeen, Y., Blaisdell, J., & Hamdy, M. (1980). A model for ear corn drying. *American Society of Agricultural Engineers* , 1261-1271.

Trujillo, F. J., & Pham, Q. .. (2006). A computational fluid dynamic model of the heat and moisture transfer during beef chilling. *International Journal of Refrigeration* , 998-1009.

Xia, B., & Sun, D. (2002). Applications of computational fluid dynamics (CFD) in the food industry: a review. *Computers and Electronics in Agriculture* , *34*, 5-24.