

**THIN LAYER DRYING OF COB MAIZE USING A NATURAL  
CONVECTION SOLAR TUNNEL DRYER**

By

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Master of Engineering in Agricultural Engineering

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**DECLARATION**

I, **MUKWANGOLE MUKUWA** do hereby declare that the contents in this dissertation are my original work and have not been previously submitted to any University for the award of a degree or any other qualification.

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**CERTIFICATE OF APPROVAL**

This dissertation submitted by **MUKWANGOLE MUKUWA** is approved as fulfilling the requirements for the award of the degree of Master of Engineering in Agricultural Engineering at the University of Zambia.

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## ABSTRACT

A semi- cylindrical natural convection Solar Tunnel Dryer (STD) was used for experiments to dry partially field- dried maize cobs with a moisture content of about 30 % wet basis to a safe storage moisture content of 12.5 % wet basis. Air temperatures ranging from 15.8 °C to 20.8 °C above ambient temperature were recorded in the collector unit. The presence of Aflatoxins was investigated for maize dried in the Solar Tunnel Dryer (STD), Open- Sun Drying (OSD) and partially field-dried maize gotten Straight From the Field (SFF). The chimney performance was also evaluated. Drying time was examined with moisture content ratio as exponential and polynomial correlations. Fourteen different mathematical models available in literature were compared using their coefficient of determination to estimate solar drying curves.

Based on statistical analysis results, Midilli drying model has shown a better fit to the experimental drying data of maize with a coefficient of determination  $R^2=0.99912$  as compared to other models. The Aflatoxins concentration levels was 8.37 parts per billion (ppb) for maize dried in STD and 11.57 ppb for OSD maize, respectively. The maize which was partially field- dried and tested for Aflatoxins had a concentration of 8.63 ppb. In Zambia, Aflatoxins concentrations above 10 ppb are not allowable. Acceptable Aflatoxins concentrations in the USA is 20 ppb whereas in the European Union countries concentrations of 4 ppb are allowed for ready to eat corn and 10 ppb for corn destined for further processing.

In one of the experiments, it took 30 hours to obtain a moisture content of 12.57 % from an initial moisture content of 20.98 % wet basis as compared to 46 hours for OSD. In this experiment, the results show that the designed STD reduced the drying time of maize by 16 hours as compared to OSD. For air movement to take place, the buoyant pressure head in the chimney should be positive. Average values of buoyant pressure head ranged from  $0.24645 \text{ Nm}^2$ ,  $0.44859 \text{ Nm}^2$  and  $0.10819 \text{ Nm}^2$  for all the experiments carried out.

## **DEDICATION**

This research work is dedicated to my family members for their prayers, encouragement and unconditional support during the study period. May the Almighty God bless and protect them all for many more years to come.

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## TABLE OF CONTENTS

DECLARATION .....	ii
CERTIFICATE OF APPROVAL .....	iii
ABSTRACT .....	iv
DEDICATION .....	v
ACKNOWLEDGEMENTS .....	vi
TABLE OF CONTENTS .....	vii
LIST OF FIGURES .....	xiii
LIST OF TABLES .....	xvi
NOMENCLATURE .....	xvii
LIST OF ABBREVIATIONS .....	xx
CHAPTER I .....	1
1.0 INTRODUCTION .....	1
1.1 Background .....	1
1.2 Post-harvest losses .....	3
1.3 Statement of the problem .....	3
1.4 Objectives of the research .....	3
1.4.1 Main objective .....	3
1.4.2 Specific objectives .....	3
1.5 Significance of the research .....	4
1.6 Scope of the study .....	4
1.7 Closing remarks .....	4
CHAPTER II .....	6
2.0 LITERATURE REVIEW .....	6
2.1 Post-harvest losses of maize .....	6
2.2 Significance of open-sun drying .....	7
2.3 Purposes of drying .....	8

2.4	Open- sun drying versus solar drying .....	9
2.5	Types of dryers .....	11
2.5.1	Adiabatic dryers .....	12
2.5.1.1	Cabinet dryers .....	12
2.5.1.2	Tunnel dryers .....	12
2.5.1.3	Kiln dryers .....	13
2.5.1.4	Spray dryers .....	13
2.5.1.5	Foam-mat dryers .....	14
2.5.2	Solid surface type dryers .....	14
2.5.2.1	Drum dryers .....	14
2.5.2.2	Vacuum shelf dryers .....	14
2.5.2.3	Continuous vacuum dryers .....	15
2.5.3	Systematic classification of dryers .....	15
2.5.3.1	High temperature dryers .....	15
2.5.3.2	Low temperature dryers .....	16
2.6	Classification of solar- energy drying systems .....	16
2.6.1	Passive solar drying systems .....	17
2.6.1.1	Open-to-sun drying .....	17
2.6.1.2	Natural- circulation solar- energy crop dryers .....	18
2.6.1.3	Integral- type natural- circulation solar energy energy dryers .....	19
2.6.2	Passive solar cabinet dryers .....	20
2.6.3	Natural- circulation greenhouse dryers .....	20
2.6.4	Large scale integral- type passive tropical solar dryer .....	21
2.6.5	Distributed- type natural- circulation solar- energy	

dryers .....	21
2.6.6 Mixed- mode natural- circulation solar energy dryers .....	23
2.7 Active solar drying systems .....	23
2.8 Fundamentals of drying .....	23
2.8.1 The drying process .....	24
2.8.1.1 Internal conditions .....	25
2.8.1.2 External conditions .....	25
2.9 Drying kinetics .....	25
2.9.1 Constant drying rate period.....	26
2.9.2 Falling drying rate period .....	27
2.10 Solar chimney and estimation of buoyancy pressure .....	28
2.11 Thin layer drying and mathematical modeling .....	30
2.11.1 Mathematical modeling of solar drying curves.....	31
2.12 Solar tunnel dryer .....	32
2.13 Basic design equations .....	34
2.14 Mycotoxin contamination of maize grains .....	35
2.15 Closing remarks .....	36
CHAPTER III .....	37
3.0 DESIGN AND CONSTRUCTION OF THE SOLAR TUNNEL DRYER .....	37
3.1 Design considerations for the solar tunnel dryer .....	37
3.1.1 Design conditions and assumptions for construction for construction of the solar tunnel dryer .....	37
3.1.2 Design description of the solar tunnel dryer .....	38
3.1.3 Design calculations for the solar tunnel dryer .....	38
3.1.4 Construction of the solar tunnel dryer .....	43

3.1.5	Description of the solar tunnel dryer and its components	45
	.....	
3.1.5.1	The collector unit	45
3.1.5.2	The drying unit	46
3.1.5.3	The chimney unit	46
3.2	Mode of operation of the dryer	46
3.3	Closing remarks	47
CHAPTER IV	.....	48
4.0	METHODOLOGY	48
4.1	Experimental site and procedures	48
4.2	Determination of the initial moisture content of the maize cobs	54
	.....	
4.3	Maize drying experiments	54
4.4	Determination of Aflatoxins	56
4.5	Mathematical modeling of solar drying curves	57
4.6	The chimney unit buoyancy pressure head	57
4.7	Closing remarks	58
CHAPTER V	.....	59
5.0	EXPERIMENTATION AND RESULTS	59
5.1	Comparison of time taken to dry maize in STD and OSD	59
5.2	Variation of temperature versus solar radiation during drying in all experiments	61
5.3	Variation of relative humidity versus solar radiation during the drying period for all the experiments	65
5.4	Thin layer modeling	69
5.5	Comparison of predicted and experimental moisture ratio during the drying period	73

5.6	Performance of solar chimney .....	75
5.6.1	Comparison of ambient and chimney temperature during the drying period .....	78
5.7	Aflatoxins levels in maize .....	81
5.8	Closing remarks .....	81
CHAPTER VI .....		82
6.0	DISCUSSION .....	82
6.1	Comparison of time taken to dry maize in STD and OSD .....	82
6.2	Variation of temperature versus solar radiation during drying in all experiments .....	83
6.3	Variation of relative humidity versus solar radiation during the drying period for all the experiments .....	84
6.4	Thin layer modeling .....	85
6.5	Comparison of predicted and experimental moisture ratio during the drying period .....	85
6.6	Performance of solar chimney .....	86
6.7	Aflatoxins levels in maize .....	86
6.8	Closing remarks .....	86
CHAPTER VII .....		87
7.0	CONCLUSIONS AND RECOMMENDATIONS .....	87
7.1	Conclusions .....	87
7.1.1	To design and fabricate the natural convection Solar Tunnel Dryer .....	87
7.1.2	To carry out thin layer drying of maize cobs and finding an appropriate mathematical model .....	87
7.1.3	To compare the presence of Aflatoxins in maize dried by Solar Tunnel Dryer and Open- Sun Drying .....	87

7.1.4	To evaluate the performance of the chimney on the natural convection dryer .....	88
7.2	Recommendations .....	88
7.3	Closing remarks .....	88
REFERENCES .....		89
Appendix I: Averages of meteorological data used for design of the dryer .....		95
Appendix II: Collector and drying units .....		96
Appendix III: Chimney unit .....		97
Appendix IV: Drying tray unit .....		98
Appendix V: Dryer platform .....		99
Appendix VI: Air guide .....		100
Appendix VII: Model view of dryer .....		101
Appendix VIII: Solar Tunnel Dryer- List of materials .....		102

## LIST OF FIGURES

Figure 2.1: Postharvest losses pipeline for maize. ....	7
Figure 2.2: Open sun drying. ....	10
Figure 2.3: Typical solar dryer designs. ....	11
Figure 2.4: Classification of dryers and drying modes .....	17
Figure 2.5: Schematic illustration of drying rate periods: 1-2 the heating period (constant moisture content); 2-3 the constant rate drying period; 3 the critical moisture content; 3-4 the first falling rate period; 4-5 the second falling rate period.....	26
Figure 2.6: Air heating flat-plate solar energy chimney .....	28
Figure 2.7: Greenhouse solar chimney .....	30
Figure 2.8: The AIT Solar Tunnel Dryer.....	33
Figure 3.1: Front view of the Solar Tunnel Dryer.....	43
Figure 3.2: Side view of the Solar Tunnel Dryer .....	43
Figure 3.3: End view of the Solar Tunnel Dryer.....	44
Figure 3.4: The open dryer showing the solar absorber painted black and the drying tray .....	45
Figure 3.5: Air flow in the Solar Tunnel Dryer .....	47
Figure 4.1: Maize crop. University of Zambia, Lusaka (2017) .....	48
Figure 4.2: Pictorial view of data logger connected to laptop and probes extending out .....	49
Figure 4.3: Pictorial view of pyranometer .....	50
Figure 4.4: Pictorial view of cables extending to the dryer .....	51
Figure 4.5: Pictorial view of probe measuring air temperature at collector exit .....	51

Figure 4.6:	Pictorial view of probe measuring air temperature at dryer exit ....	52
Figure 4.7:	Pictorial view of probe measuring air temperature at chimney exit.....	53
Figure 4.8:	Experimental set-up of the solar tunnel dryer and the equipment: collector unit, drying unit, bare flat- plate chimney unit, data logger, computer and solar pyranometer .....	53
Figure 4.9:	Maize being dried in the Solar Tunnel Dryer (STD) .....	55
Figure 4.10:	Open-Sun Drying experiment (control).....	56
Figure 5.1:	Reduction of moisture content in OSD and STD (Experiment 1) .....	59
Figure 5.2:	Reduction of moisture content in OSD and STD (Experiment 2) ...	60
Figure 5.3:	Reduction of moisture content in OSD and STD (Experiment 3) ...	61
Figure 5.4:	Variation of temperature and solar radiation with time of the day (Experiment 1) .....	62
Figure 5.5:	Variation of temperature and solar radiation with time of the day (Experiment 2) .....	63
Figure 5.6:	Variation of temperature and solar radiation with time of the day (Experiment 3) .....	64
Figure 5.7:	Relationship of relative humidity against solar radiation over the drying period (Experiment 1) .....	66
Figure 5.8:	Relationship of relative humidity against solar radiation over the drying period (Experiment 2) .....	67
Figure 5.9:	Relationship of relative humidity against solar radiation over the drying period (Experiment 3) .....	68
Figure 5.10:	Regression analysis for Midilli mathematical model (Experiment 1) .....	74

Figure 5.11: Regression analysis for Midilli mathematical model (Experiment 2) .....	74
Figure 5.12: Regression analysis for Midilli mathematical model (Experiment 3) .....	75
Figure 5.13: Variation of buoyant pressure and insolation with drying time (Experiment 1).....	76
Figure 5.14: Variation of buoyant pressure and insolation with drying time (Experiment 2) .....	77
Figure 5.15: Variation of buoyant pressure and insolation with drying time (Experiment 3) .....	78
Figures 5.16: Variation of ambient and chimney temperature during drying (Experiment 1) .....	79
Figures 5.17: Variation of ambient and chimney temperature during drying (Experiment 2) .....	79
Figures 5.18: Variation of ambient and chimney temperature during drying (Experiment 3) .....	80

## **LIST OF TABLES**

Table 1: Mathematical models given by various authors for the solar drying curves .....	31
Table 2: Conditions and assumptions for dryer design.....	37
Table 3: Regression analysis for Experiment 1.....	69
Table 4: Regression analysis for Experiment 2.....	71
Table 5: Regression analysis for Experiment 3.....	72

## NOMENCLATURE

$K_m$	Mass transfer coefficient of water vapour ( $\text{kg s}^{-1} \text{m}^{-2}$ )
$K_f$	Thermal conductance of air film ( $\text{W m}^{-2} \text{K}^{-1}$ )
$L$	Latent heat of vaporization ( $\text{J kg}^{-1}$ )
$R_o$	Universal gas constant ( $\text{J mol}^{-1} \text{K}^{-1}$ )
$P_v$	Water vapour pressure in product ( $\text{Nm}^{-2}$ )
$P_{va}$	Vapour pressure of drying air ( $\text{Nm}^{-2}$ )
$T$	Absolute temperature (K)
$T_a$	Drying air temperature (K)
$T_s$	Crop surface temperature (K)
$dw/d_t$	Drying rate (kg/s)
$\Delta P_b$	Buoyancy pressure ( $\text{Nm}^{-2}$ )
$g$	Acceleration due to gravity ( $\text{ms}^{-2}$ )
$H$	Height of chimney (m)
$\rho_{am}$	Density of ambient air ( $\text{kgm}^{-3}$ )
$\rho_{ch}$	Density of chimney air ( $\text{kgm}^{-3}$ )
$X_R$	Dimensionless moisture ratio
$X_t$	Moisture content at given time
$X_0$	Initial moisture content
$X_e$	Equilibrium moisture content
$m_w$	Amount of moisture to be removed from a product (kg)
$m_p$	Initial mass of product to be dried (kg)
$M_i$	Initial moisture content, % wet basis

$M_f$	Final moisture content, % wet basis
$Q$	The amount of heat energy required for the drying process (kJ)
$h_{fg}$	Latent heat of evaporation kJ/kg H <sub>2</sub> O
$h_{fg}^*$	Latent heat of vapourisation (kJ)
a	2.1
b	-170
ERH	Equilibrium relative humidity (%)
k	$6.6612 * 10^{-5}$
N	1.9677
C	42.143
$M_e$	Final equilibrium moisture content
$a_w$	Water activity
E	Total heat energy (kJ)
$\dot{m}$	Mass flow rate of air (kg/hr)
$h_f$	Final enthalpy of drying air (kJ/kg dry air)
$h_i$	Initial enthalpy of ambient air (kJ/kg dry air)
$t_d$	Drying time (hr)
$m_{dr}$	Average drying rate (kg/hr)
$w_i$	Initial humidity ratio (kg of water/kg of dry air)
$w_f$	Final humidity ratio (kg of water/kg of dry air)
$A_c$	Collector area (m <sup>2</sup> )
I	Total global radiation received on the horizontal surface during the drying period (kJ/m <sup>2</sup> )

$\eta$  Collector efficiency

$V_a$  Volumetric airflow rate ( $\text{m}^3/\text{hr}$ )

## LIST OF ABBREVIATIONS

d.b.	Dry basis		SUBSCRIPTS
w.b.	Wet basis	Exp	Experimental
STD	Solar tunnel dryer	Pred	Predicted
OSD	Open sun drying	d	Drying unit exit
MC	Moisture content	c	Collector unit exit
ppb	Parts per billion	ch	Chimney unit exit
IITA	International Institute for Tropical Agriculture	e	Equilibrium
SSA	Sub- Sahara Africa	i	Initial moisture content
FAO	Food and Agriculture Organization	f	Final moisture content
PHLs	Post- harvest losses		
APHLIS	African post harvest loss information system		
UV	Ultra violet		
MR or XR	Dimensionless moisture ratio		
$M_i$	Initial moisture content		
$M_f$	Final moisture content		
$T_{am}$	Ambient temperature		
$RH_{am}$	Ambient relative humidity		

## CHAPTER I

### 1.0 INTRODUCTION

The background to the study, general definition of Post-Harvest Losses, the statement of the problem, objectives of the research, significance of the research and the scope of study are presented in this chapter.

### 1.1 Background

Cereal grains have been and will continue to be a major source of food for humans and animals throughout the world. According to Golob et al. (2004), maize is the third most widely grown crop after rice and wheat. These are the world's most widely cultivated crops and the foundation of world food security (Suleiman et al., 2013). Leonard and Martin (1963), reported that maize is the most important cereal the world over as its products can and have been used for various purposes such as; human food, animal feed, alternative medicine, chemicals, bio fuels, ornamentals, animal bedding from the cobs, etc. From time immemorial, the medicinal value of maize cannot be overemphasized as it has been used to pacify kapha, pitta, anorexia, general debilities, emaciation and haemorrhoids. As a potent antioxidant, it guards the body from harm by free radicals responsible for cellular damage and/or cancer (Kumar and Jhariya, 2013). The major nutrient of corn silk is potassium that is a powerful diuretic. Corn silk improves blood pressure and supports liver functioning as well as producing bile. Roots, leaves and corn silk as decoction are used for bladder while the decoction of cob as tea is used for stomach complaints (Kumar and Jhariya, 2013).

Maize is the most widely grown and consumed staple crop in Africa with more than 300 million people depending on it as their main food source in the continent (M'mboyi et al., 2010). Corn meal is made into a thick porridge in many cultures called sadza, nshima, ugali, and mealie pap. Pollens and seeds are the nutritious and edible parts of maize. Seeds may be consumed in raw and cooked form that serves as a good source of carbohydrates. Maize contains vitamin B- complex such as B<sub>1</sub> (thiamine), B<sub>2</sub> (niacin), B<sub>3</sub> (riboflavin), B<sub>5</sub> (panthothenic acid) and B<sub>6</sub> that makes it

commendable for hair, skin, digestion, heart and the brain (Kumar and Jhariya, 2013).

According to M'mboyi et al. (2010), 24 million households in East and Southern Africa depend on maize as a staple food and it is grown over an area of 15.5 million hectares. Blackie (1990), reported that a third of the total cultivated area in East and Southern Africa is taken up by maize.

In Zambia, maize crop is intensively and extensively cultivated in all the agro-ecological zones of the country. There are two seasons in Zambia: the dry winter season (May to October) when mainly vegetables and irrigated wheat are grown and, the wet summer season (November to April) when maize and all other row crops are cultivated. Winter maize is mostly grown under irrigation.

Jazayeri and Amani (2004), reported that maize accounts for over 30 % of lower-house income, contributing 60 % of dietary calories and 50 % of protein intake. Zambia has a land of 752,618 km<sup>2</sup> with a population of over 15 million people of which over 64 % live under extreme poverty and 40 % of children suffer from stunted growth (World Bank, 2016). Day et al. (2009), stated that agriculture employs a large portion of the labour force and 32 % of the country's land is taken for agricultural production. Sitko et al. (2014), reported that small scale farmers i.e. (having < 2ha of land) account for 70 % of the farms yet this does not account for a third of agricultural production. Small holder farmers harvest a number of different crops, but maize is a dominant one amongst these farmers with 86 % of the farmers growing the crop (Weitz et al., 2015). It accounts for 48 % of the land under agriculture according to (FAO, 2014) .

When the maize reaches physiological maturity (moisture content is about 20- 30 %), it is normally left in the field to dry. During this period, pests, rodents, wild and domestic animals, and birds may attack the crop. Other than the above highlighted issues, unexpected rains or bad weather may prevail which may lead to rewetting of the dried crop. This might cause mould and fungal attack which may lead to mycotoxins and Aflatoxins development. These are the situations faced by most maize farmers in Zambia who rely on Open- Sun Drying of their crop.

## **1.2 Post-harvest losses**

According to Hodges et al. (2011), Post-Harvest Losses (PHLs) refers to the measurable qualitative and quantitative food loss along the supply chain beginning from harvest to the final consumer. It occurs in two forms namely, quantitatively and qualitatively. In quantitative PHLs, there is a decreased volume and weight in the food while qualitative PHLs are characterised by diminished nutrient value, undesirable changes in taste, odour, and textural change occurs (Cherotich, 2016).

## **1.3 Statement of the problem**

All small-scale African farmers rely on Open- Sun Drying to ensure that their crop is sufficiently dry for storage (Hodges, 2014). If weather conditions are too cloudy, humid or even wet then the crop will not be dried sufficiently and losses will be high.

As a result of the challenges associated with Open-Sun Drying, an improved technology in utilizing solar energy for drying grain is the use of solar dryers where the air is heated in a solar collector and then passed through beds of grain. In this research, a Solar Tunnel Dryer has been designed to investigate how it can help to reduce postharvest losses associated with drying.

## **1.4 Objectives of the research**

### **1.4.1 Main objective**

To investigate the performance of a natural convection Solar Tunnel Dryer in the drying of physiologically matured maize cobs.

### **1.4.2 Specific objectives**

- 1) To design and fabricate the natural convection Solar Tunnel Dryer.
- 2) To carry out thin layer drying of maize cobs and find an appropriate thin layer model.
- 3) To compare the presence of Aflatoxins levels in maize dried by Solar Tunnel Dryer and Open-Sun Drying.
- 4) To evaluate the performance of the chimney on the natural convection dryer.

## **1.5 Significance of the research**

In Sub-Sahara Africa, small scale farmers have continued to rely on Open-Sun Drying to dry their maize crop. Despite the fact that the sun is always there to help in drying of crops in conjunction with wind, unseasonal rains may wet a crop which is almost dried and cause mould and fungal attacks. This leads to development of Aflatoxins and mycotoxins. Animals, birds and insects can attack the crop. Because the crop remains too long in the field, it becomes vulnerable to theft. The maize takes a long time to dry when left in the field.

The design of the Solar Tunnel Dryer aims to ease these problems as it will quicken the rate of drying. Drying will be more complete under an enclosed environment. Infestation from dust, birds, animals and unseasonal rains will be mitigated.

This research will also help to add to the existing knowledge on solar drying technology. This technology can be made to trickle down to the small scale farmers who contribute significantly to the total grain produced in the country through engaging the Ministry of Agriculture as unseasonal rains have become more prevalent. The research is of significance because the Solar Tunnel Dryer is relatively simple to fabricate, easy to operate and made from locally available materials.

## **1.6 Scope of the study**

This study involved production of a maize crop by growing it under rain-fed conditions and later used for experiments in Open-Sun Drying and Solar Tunnel Dryer drying once physiological maturity was reached. The dryer was tested during the period from mid May 2017 through early June 2017 after the crop had partially dried in the field. Design data such as air temperature, wind velocity and relative humidity for a yearly average was used so that drying could be done throughout the year. It is also envisaged that the dryer could also be used to dry other crops. A thin layer model for drying maize was validated from amongst those existing in literature.

## **1.7 Closing remarks**

This chapter has given an introduction to the topic which focuses on preservation of agricultural produce that has reached physiological maturity. The problems associated with Open-Sun Drying have been highlighted hence the mitigation

measures of using a Solar Tunnel Dryer to investigate its performance. The significance of the research and scope of study have also been given.

The next Chapter deals with Literature Review.

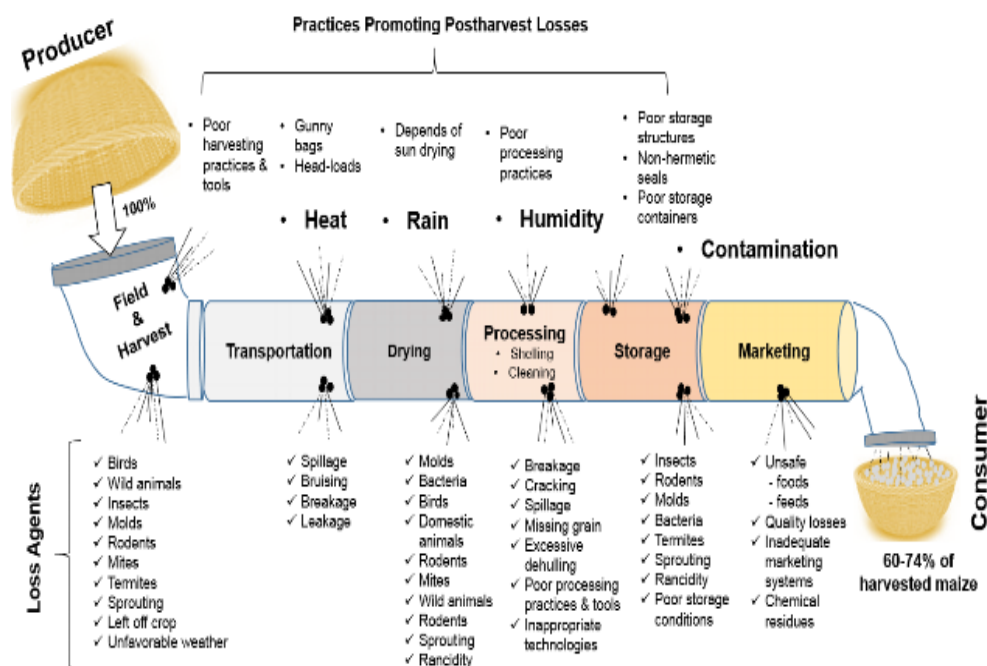
## **CHAPTER II**

### **2.0 LITERATURE REVIEW**

In this Chapter, Post-Harvest Losses of maize are covered while the significance of Open- Sun Drying is also presented. The purposes of drying and the comparison of Open- Sun Drying and Solar Drying are outlined. Types of dryers and the classification of solar energy drying systems are presented. The fundamentals of drying, drying kinetics and solar chimney are also given. Thin layer drying and mathematical modelling equations are introduced. The determination of the presence of mycotoxins, basic dryer design equations and the Solar Tunnel Dryer are all introduced.

### **2.1 Post- harvest losses of maize**

Post-Harvest Losses (PHLs), is the grain loss which occurs after separation from the site of growth or production to the point where the grain is prepared for consumption (Boxall, 1986). De Lucia and Assennato (1994), describe PHLs as measurable quantitative, qualitative and economics of grain loss across the supply chain. According to data from APHLIS, maize has the highest PHLs in the Sub-Saharan Africa at 18.0 % as compared to other cereals such as rice (12.5 %), sorghum (12.5 %) and millet (9.6 %). PHLs for maize in Zambia were pegged at 14.9 % in 2007. Figure 2.1 summarises PHLs of maize at different stages of the crop value chain.



**Figure 2.1: Postharvest losses pipeline for maize. Modified from Bourne (1977) and Abass et al. (2014).**

To mitigate the problems associated with Open- Sun Drying, a Solar Tunnel Dryer has been designed to ensure sufficient quick drying, thereby reducing drying losses in the field, and improve the quality of the dried product.

## 2.2 Significance of open- sun drying

Drying is one of the oldest and most widely used methods of food preservation. In many rural locations in Zambia and other developing countries, grid-connected electricity and other supplies of non-renewable sources of energy are unavailable, unreliable or, too expensive for farmers. In such areas, crop drying systems that employ the use of motorized fans/ or electrical heating cannot be used. Large initial and running costs of fossil- fuel powered dryer technologies are rarely adopted by small-scale farmers (Ekechukwu and Norton, 1999a).

In tropical countries, for at least several months of the year, the mean level of insolation upon the ground is more than 0.5 kW/m<sup>2</sup> (measured as a mean over the hours of daylight). The heat available therefore, assuming a 12 hour day, is 21.6 MJ/m<sup>2</sup>, a quantity theoretically sufficient to evaporate 9 kg of water. Even today, Open- Sun Drying of grain remains the most common drying method in tropical

developing countries. It is first employed when the crop is standing in the field prior to harvest; maize cobs may be left on the standing plant for several weeks after attaining maturity. Although not requiring labour for maize left standing or other inputs, field drying may render the grain subject to insect infestation and mould growth, prevent the land being prepared for the next crop and is vulnerable to theft and damage from animals. In cases where stooking (bunching of the maize) is done, the drying may not be uniform since the maize stalks on the outside are exposed to more air and sunlight than the stalks in the middle of the stook. This may lead to maize in the middle of the bunch developing mould growth.

Drying in the field may also be carried out after harvest with the harvested plants laid in stacks with the grain, maize cobs or panicles raised above the ground and exposed directly to the sun. Drying on flat exposed surfaces is the most common way of drying grain after harvesting and threshing. For drying small amounts on the farm, grain may be spread on any convenient area of land. Contamination with dirt cannot be easily avoided with this method and cleaner dried grain can be obtained by drying the grain on plastic sheets, preferably black.

Where there is a need to dry large quantities of grain during the season, purpose-constructed drying floors are commonly used. The floors are usually made from concrete or bricks as these normally provide a smooth and hard wearing surface. The floor should be channeled to allow for quick drainage.

Cob maize can also be dried in a crib which also serves as a storage structure (FAO, 1986). Natural ventilation ensures that the grains are dried to the required moisture content. It is important that the loaded crib is exposed to adequate air flow. The rate and uniformity of drying are controlled by the relative humidity of the air and the ease with which air can pass through the bed of cobs. Air movement in the crib is largely attributable to the width of the crib.

### **2.3 Purposes of drying**

Despite the fact that in many parts of Africa certain crops can be produced throughout the year, the major food crops such as cereal grains and tubers, including potatoes, are normally seasonal crops. For this reason, the food produced in one harvest period, which may last for only a few weeks, must be stored for gradual

consumption until the next harvest, and seed must be held for the next season's crop. Further, in a market that is liberalized, the value of any surplus crop tends to rise during the off-season period, provided that it is in a marketable condition.

According to Prescott and Proctor (1937), drying by natural or artificial means ensures that food attain a state of preservation mostly because of its lowered moisture content. The major agents of food spoilage are; enzymes in the food, yeasts, moulds, bacteria and the enzymes elaborated by the latter three. If the water content is sufficiently low in the food, the activities of bacteria, yeasts, moulds and enzymes is greatly inhibited. The moisture requirements for germination and growth for any organism can be stated in terms of water activity. Stoffel (1974), stated that water activity is the ratio of water vapor pressure in the foodstuff to the vapor pressure of pure water at the same temperature. In general, bacteria have a higher water activity requirement than yeasts and moulds, and yeasts have a higher requirement than moulds. This means relatively dry food is more likely to be spoiled by moulds than by yeasts and bacteria. Stewart and Amerine (1973), stated that very few moulds grow on foods with a water activity of 0.70 or below: hence, microorganisms are not likely to spoil foods with a water activity below 0.70.

Grains are dried and consumed in large quantities around the world. A crop may require drying so that it can be further processed. For instance, many grains are dried so that they can be ground into flour. Fresh crops are sometimes dried so that a new product, distinctly different from its original form, can be produced. Lowering transportation and storage costs are other reasons drying of agricultural products is encouraged.

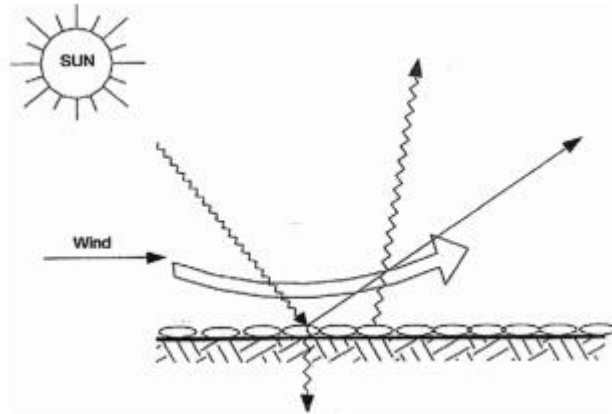
#### **2.4 Open-sun drying versus solar drying**

Sun- Drying has been used universally as a method of preserving agricultural produce, but it is not universally applicable to a common standard of efficiency and reliability.

Even though sun drying is still by far the most common method of drying, it does have several inherent disadvantages. Usually, the unprotected crop can be damaged by unseasonal rains, contaminated by dirt and animals and/or eaten by birds and insects. In addition, the product may be over dried or under dried as the drying

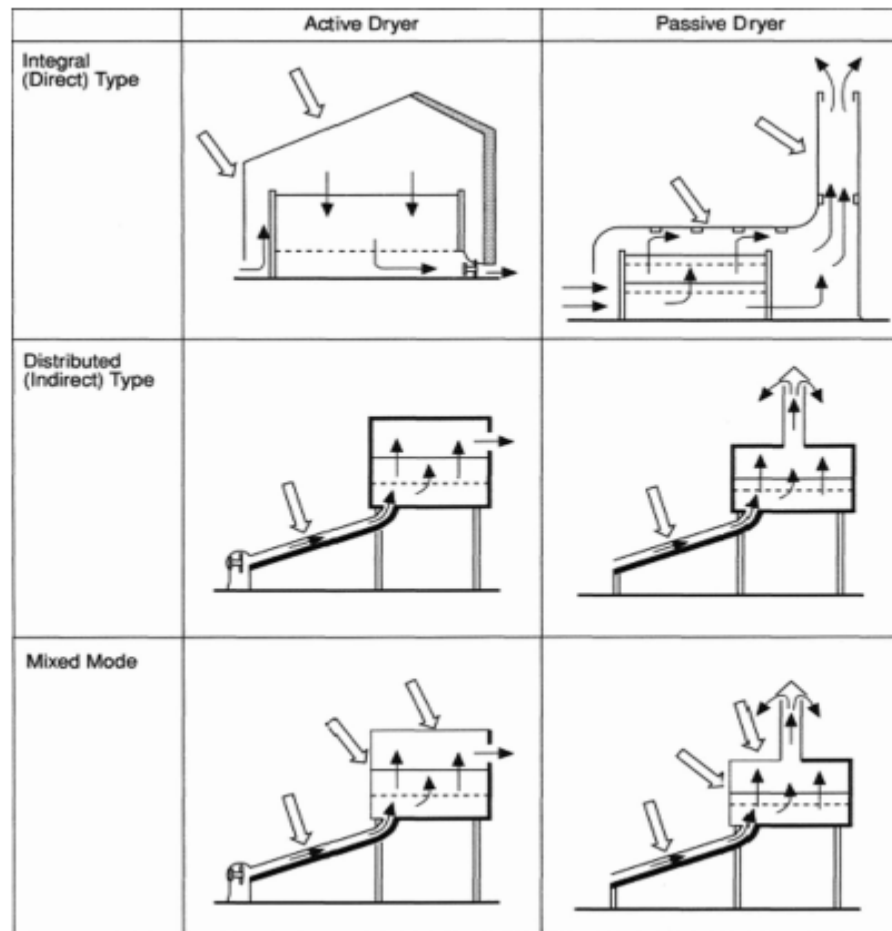
process is not controlled. The temperatures attained during sun drying are usually lower than in a solar dryer and therefore, drying times are longer. Open sun-drying normally results in poorer final product quality because of crop discoloration caused by enzymic and non-enzymic browning, UV radiation and the formation of moulds (Fuller).

Figure 2.2 depicts how the process of Open-Sun Drying takes place.



**Figure 2.2: Open sun drying. Source:(Prakash and Kumar, 2013)**

On the other hand, the temperature of the air surrounding the product in a solar dryer is raised above the ambient air temperature. The temperature of the product may also be raised by direct absorption of solar radiation, depending on the type of solar dryer. Since the temperatures in a solar dryer are normally higher than in open-sun drying, less time is usually required to dry a given product and its quality is good. Further, crop losses and spoilage from rain and animals are prevented because the crop is protected within the solar dryer. Figure 2.3 shows typical solar dryer designs.



**Key:**



*Figure 2.3: Typical solar dryer designs. Source: (Prakash and Kumar, 2013)*

## 2.5 Types of dryers

In industry, many types of dryers have been developed for the dehydration of food. The principle governing the choice of dryer type is the nature of the commodity to be dried, the desired form of the finished product, economics and operating condition (Loesecke von, 1955). Dryers are either directly or indirectly heated. In dryers which are directly heated, heated air or hot gases from combustion mixed with air, are passed across, through or around products to be dried (Joslyn, 1963). The sensible heat in the heated air furnishes the latent heat for moisture evaporation and the cooled gases then convey the vapor away from the product.

According to Desrosier and Desrosier (1977), dryers have been classified into two basic categories:

- 1) Adiabatic in which heat is carried into the dryer by hot air. The air gives up the heat and carries out the water vapor.
- 2) Heat transfer through a solid surface, i.e., the heat is transferred to the product through direct contact with the metal plate which also supports the product.

### **2.5.1 Adiabatic dryers**

There are five dryer types which fall under the category of adiabatic. These are cabinet, tunnel, kiln, spray and foam-mat.

#### **2.5.1.1 Cabinet dryers**

Cabinet dryers are usually small, insulated units with a heater, circulating fan, and shelves to hold the product to be dried. However, in large dryers the trays are placed on permanent supports in the dryer. The small dehydration units sold for home use are examples of this type of dryer. Commercially, different designs are used, but the general procedure is to force heated air over multiple trays. Cabinet dryers are usually the least expensive dryers to build, easy to maintain, and commonly used for laboratory studies in the dehydration of vegetables and fruits, and in small scale and seasonal commercial operations.

#### **2.5.1.2 Tunnel dryers**

Tunnel dryers are a large-scale modification of the cabinet dryer concept. They consist of tunnels of 10 to 20 m long into which trucks containing the trays of the product to be dried are placed. New carts of undried product are loaded at one end of the tunnel as carts of dried product are removed from the other end. In these dryers air flow may be parallel, counter or a combination of the two. Hot air is blown across the trays.

The co-current and the counter current dryer tunnels are combined into one unit in the combination dryer type. To take advantage of the high initial rate of drying, the product is first placed in a co-current tunnel and then in a counter current tunnel to

get a very dry end product. Desrosier and Desrosier (1977), reported that generally the counter flow tunnel uses less heat and produces a drier product than a co-current tunnel. Continuous tunnel dryers exist that use moving conveyors.

### **2.5.1.3 Kiln dryers**

Kiln dryers are commonly two-story buildings in which the upper floor is composed of narrow slats on which the food product is spread. Hot gas is produced by a furnace or stove on the first floor and passes through the product by natural convection or with the aid of a fan (Kwendakwema, 1983). A relatively long time of drying is required despite the material being turned and stirred frequently (Desrosier and Desrosier, 1977).

### **2.5.1.4 Spray dryers**

Although spray dryers are adiabatic, they differ from the previous three types in that they are used to dry solutions, pastes or slurries. The product to be dried is sprayed into a stream of heated air. Water evaporates into the air leaving the dry particles to be collected. Spray dryers can be divided into five principle categories in accordance with the direction of spray dispersal and relative direction of the drying air. These categories are:

- 1) horizontal co-current,
- 2) simple vertical downward co-current,
- 3) complex vertical downward -co-current,
- 4) vertical upward co-current and ,
- 5) vertical counter current (Loesecke von, 1955).

To optimize drying, droplets should be small and uniform in size. Thus special procedures must be used to insure that atomization is satisfactory. Special techniques are required for the collection of the powder particles which are small and move easily within an air stream. Collection chambers or special filters are normally used. Actual operations are more complex, and many different configurations are available (Wilhelm, 2004).

### **2.5.1.5 Foam-mat dryers**

Foam-mat dryers are used primarily for liquids, which are prefoamed by whipping. Low levels of whipping agents are added to the liquids. By foaming a liquid, enormous surface areas are exposed for quick moisture removal which also permits the use of lower drying temperatures. The foam is deposited in a uniform layer on a perforated tray or belt through which hot air is blown. Foam layers of foods can be dried to about 2 to 3 % moisture content in approximately 12 minutes (Desrosier and Desrosier, 1977).

### **2.5.2 Solid surface type dryers**

There exist three main types of dryers that use the principle of heat transfer through a solid surface. These are drum, vacuum shelf and continuous vacuum dryers (Kwendakwema, 1983).

#### **2.5.2.1 Drum dryers**

Drum dryers may both be atmospheric or vacuum and consist of steam heated drums 1 to 2 m in diameter. They are used for drying slurries (liquids with high solids content). A thin film of the slurry is deposited on the bottom of a rotating drum as it passes through the slurry (Wilhelm, 2004). Heat is transferred through the drum wall to the product film. The slowly rotating drum is sometimes held under a vacuum and the dried product is scraped from the drum before the rotating surface re- enters the slurry. Different configurations of drum dryers exist.

#### **2.5.2.2 Vacuum shelf dryers**

Vacuum shelf dryers consist of a heavy shell to withstand a high vacuum, and a series of shelves heated by hot water, steam, hot oil or Dowtherm (Loesecke von, 1955). The product is placed inside a chamber where the pressure is reduced to produce a vacuum. As the total pressure in the chamber is very low, the partial pressure of the water vapor in the chamber is also very low. Because of this low partial pressure, a large partial pressure difference exists between the water in the product and the surroundings. As a result, water moves more readily from the product to the surrounding environment in the chamber. Vacuum dryers require expensive accessory equipment such as vacuum pumps, ejectors and condensers.

Drying at a lower temperature is possible under vacuum conditions and this characteristic is very important for products that may suffer significant flavor changes at higher temperatures (Wilhelm, 2004).

### **2.5.2.3 Continuous vacuum dryers**

In continuous vacuum dryers there is a stainless steel belt on which the product is deposited. The film on the belt passes over a heating source, which maybe a heated drum or a grid of steam coils, and heat passes through the belt to the product film (Kwendakwema, 1983).

### **2.5.3 Systematic classification of solar dryers**

All drying systems can be classified primarily according to their operating temperature ranges into two main groups of high temperature and low temperature dryers. More commonly, dryers are also classified according to heating source into fossil- fuel dryers (more commonly known as conventional dryers) and solar-energy dryers. In practice, all practically-realised designs of high temperature dryers are fossil- fuel powered, while the low temperature dryers are either fossil- fuel or solar-energy based systems.

#### **2.5.3.1 High temperature dryers**

These dryers are necessary when very fast drying is desired and the product is exposed to the drying air for a short time. Their operating temperatures are such that, if the drying air remains in contact with the product until equilibrium moisture content is reached, over drying will occur. As a result, the products are only dried to the required moisture contents and later cooled. High temperature dryers are usually classified into batch dryers and continuous-flow dryers. In the former, the products are dried in a bin and subsequently moved to storage. These are known as batch-in-bin dryers. In the later, there are heated columns through which the product flows under gravity and is exposed to heated air while descending. Since most high temperature dryers are associated with prevalent high temperatures, they are normally electricity or fossil-fuel powered (Ekechukwu and Norton, 1999a).

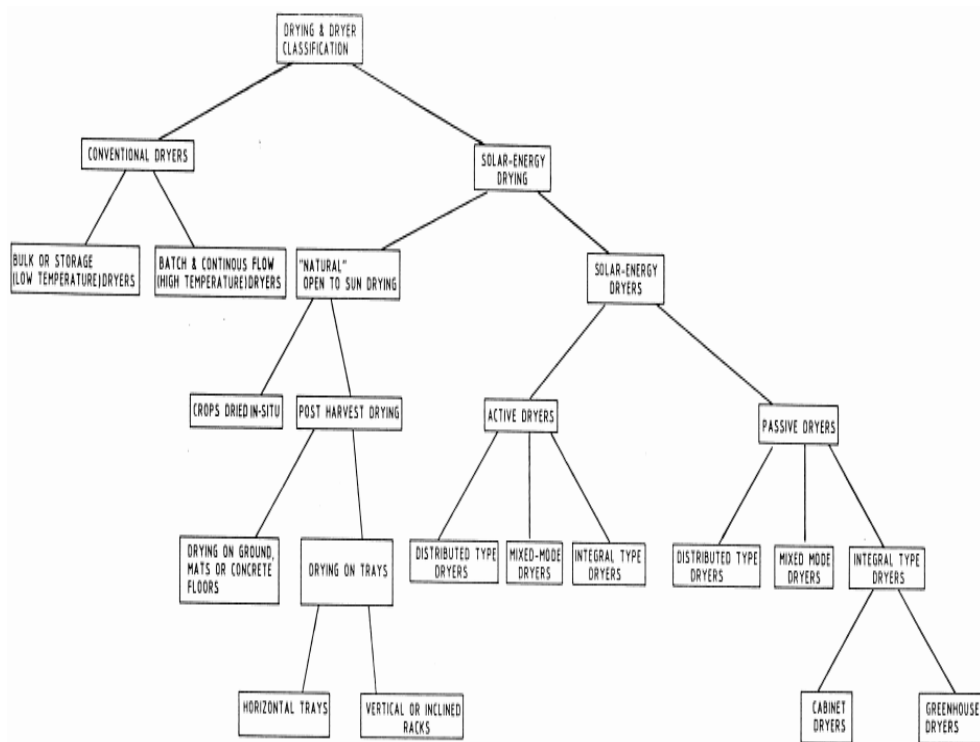
### **2.5.3.2 Low temperature dryers**

In these drying systems, the moisture content of the product is usually brought in equilibrium with the drying air by constant ventilation. These dryers do tolerate intermittent or variable heat input. Low temperature drying systems enable the drying of crops in bulk and they are suitable for long term storage systems. Their ability to accommodate intermittent heat input makes low temperature drying most appropriate for solar-energy applications. Therefore, some conventional dryers and most practically-realized designs of solar-energy dryers are of the low temperature type.

## **2.6 Classification of solar-energy drying systems**

Figure 2.4 summarises the classification of different solar-energy drying systems. Solar-energy drying systems are classified primarily according to their heating modes and the manner in which the solar heat is utilized. Broadly speaking, they can be classified into two major groups, namely:

- active solar-energy drying systems (most types of which are often termed hybrid solar dryers); and
- passive solar-energy drying systems (conventionally termed natural-circulation solar drying systems).



**Figure 2.4: Classification of dryers and drying modes. Source: (Ekechukwu and Norton, 1999a)**

There are three distinct sub-classes of either the active or passive solar drying systems that can be identified (which vary mainly in the design arrangement of system components and the mode of utilisation of the solar heat). These systems are named as:

- integral-type solar dryers;
- distributed-type solar dryers; and
- mixed-mode solar dryers.

Figure 2.4 shows the main features of typical designs of the various classes of solar-energy dryers.

## **2.6.1 Passive solar drying systems**

### **2.6.1.1 Open-to-sun drying**

Ekechukwu (1987), reported that there are two traditional approaches by which passive solar crop drying is undertaken in tropical countries. These are:

- 1) The plant bearing the crop is allowed to die, either in contact with the soil or is cut down but not removed, thus the crop is dried "in situ".
- 2) The crop is spread on the ground, mat, cemented floor or placed on either horizontal or vertical shelves exposed to solar radiation and to natural air currents. The crop is usually stirred occasionally in order to expose different parts of it to the sun and thereby encouraging more rapid removal of the saturated air.

The above processes are very rudimentary in nature. However, such techniques still remain in common use. Since the power requirements are readily available in the ambient environment (i.e. from the solar radiation and the air's enthalpy), and as little or no capital cost is required and running costs are low (often labour only), these are frequently the only commercially viable methods in which to dry agricultural produce in developing countries. Despite being utilized widely, natural open-to-sun drying techniques have inherent limitations: high crop losses ensuing from inadequate drying, fungal and insect infestation, birds and rodent encroachment and weathering effects. This process is normally intermittent being subject to cloudiness and unseasonal rains. The output is usually low and the quality is poor.

In tropical climates, sun drying poses serious practical challenges during the rain/wet season as the crop has to be removed to storage from time to time. More often than not, the quality of the dried product is degraded seriously, sometimes beyond edibility. Despite more efficient solar drying methods being developed, traditional drying methods do have the following advantages:

- 1) small capital cost;
- 2) low running cost;
- 3) independence from fuel supplies.

#### **2.6.1.2 Natural-circulation solar-energy crop dryers**

These dryers entirely depend on solar-energy for their operation. Air which is solar-heated is circulated through the crop by buoyancy forces or as a result of wind pressure. The air movement may either be purely buoyant or a combination with pressure from wind. They are named as passive dryers because air movement is

natural i.e. no fans are employed to drive air. For use in remote rural locations, natural-circulation solar-energy dryers appear the most attractive option as they are superior operationally and competitive economically to open-to-sun drying. Natural-circulation solar-energy tropical dryers are able to compete economically with traditional drying techniques because of some reasons listed below:

- 1) a smaller area of land is needed to dry similar quantities of crop that would otherwise have been dried traditionally over large land areas in the open;
- 2) high quantities and quality of crop are achieved because the product is unlikely to be infested by rodents, insects, birds, fungi and animals during drying;
- 3) higher rates of product throughput are attained as a result of the shortened period of drying;
- 4) the crop is protected from unexpected down pours of rain; and
- 5) relatively low capital and maintenance costs are incurred because of the use of readily available indigenous labour and materials for construction. This enhances the commercial viability of these dryers.

Three types of natural-circulation solar-energy drying systems have evolved namely:

- 1) integral-type natural-circulation solar-energy dryers;
- 2) distributed-type natural-circulation solar-energy dryers; and
- 3) mixed-mode natural-circulation solar-energy dryers.

### **2.6.1.3 Integral-type natural-circulation solar-energy dryers**

In this type of dryer, the crop is placed in a drying chamber which has transparent walls. This allows the penetration of the insolation much needed for the drying process. As such, the sun's radiation is absorbed directly by the product being dried. The moisture from the crop is extracted by the heat and consequently the relative humidity of the air in the drying chamber is reduced. This increases the moisture carrying capacity of the air. Additionally, the air in the chamber is expanded, thereby

generating its circulation and the subsequent removal of moisture along with the warm air.

According to Norton et al. (1987), for the same loading capacity, integral-type natural-circulation solar-energy dryers are both simpler and cheaper to construct than those of the distributed-type. These dryers do not require elaborate structures such as separate air-heating collectors and ducting. The major drawback of these dryers is their liability to overheat and the overall slow drying rates achieved as a result of poor vapour removal. These limitations can easily be overcome by the employment of a solar chimney which increases the buoyancy force imposed on the air stream, to provide a greater air flow velocity and, thus, a more rapid rate of moisture removal. Two generic types of the integral system can be identified as:

### **2.6.2 Passive solar cabinet dryers**

Jayaraman et al. (2000), stated that these dryers are best suited to drying small batches of fruits and vegetables, such as banana, pineapple, mango, potato, carrots, and French beans as well as meat and fish. The dryer consists of a shallow insulated drying chamber covered with glazing which can either be plastic or glass. The drying chamber is perforated with holes that allow ambient air to enter and exit with vapour from the product. In their work on historical review and recent trends in solar drying systems, Prakash and Kumar (2013) reported that the solar radiation passing through the transparent glazing produces low intensity heat which is trapped in the dryer causing what is known as “greenhouse effect”.

### **2.6.3 Natural-circulation greenhouse dryers**

These dryers are also known as tent dryers and are basically modified greenhouses. They are made in such a way that air vents are positioned appropriately to control air flow. Extensive glazing on the sides is characteristic for these dryers. When properly designed, greenhouse dryers allow a greater degree of control over the drying process than the cabinet dryers and are more appropriate for large scale drying. Iqbal and Ahmad (2014), described the performance of a greenhouse dryer in their work on comparative performance of selected ear-corn drying techniques. Doe et al. (1977), reported that the polythene-tent dryer is one of the later typical designs of passive greenhouse dryers. It consists of a ridged bamboo framework clad with clear

polyethylene sheet on the sun facing side and at the ends. Its back side was clad with black polyethylene sheet which was also spread on the floor to improve absorption of solar radiation. To allow access into the drying chamber, the cladding at one end was so arranged for this purpose. The clear plastic cladding at the bottom edge of the front side was rolled around a bamboo pole which could be adjusted to control air flow into the chamber, while the vents at the top of the ends served as the exit for the moist exhaust air.

Brace Research Institute (1980) glass-roof solar dryer is the earliest form of practically-realised natural-circulation solar greenhouse dryers reported. This dryer consisted of two parallel rows of drying platforms (along the long side) of galvanised iron wire mesh surface laid over wooden beams. Solar radiation over the product was allowed through a slanted glass roof over the platform.

#### **2.6.4 Large scale integral-type passive tropical solar dryer**

Ekechukwu and Norton (1999a) reported a simplified design of the typical greenhouse-type natural-circulation solar dryer which consists of a transparent semi-cylindrical drying chamber with an attached cylindrical "chimney", rising vertically out of one end, while the other end is equipped with a "door" for air inlet and access to the drying chamber. The dryer operates by the action of solar-energy impinging directly on the crop within the dryer, and no auxiliary power source is required to operate it. A vertically-hung, black absorbing curtain within the chimney and the crop absorb the solar radiation and are warmed. This in turn heats up the surrounding air. The heated air rises and flows up the chimney to the outside of the dryer while fresh replenishing air is drawn in from the other end of the dryer. This simple operation, which does not involve any additional power source, provides the circulation of air through the drier.

#### **2.6.5 Distributed-type natural-circulation solar-energy dryers**

In this drying system, the crop is not exposed directly to the solar radiation. The crop is placed on trays or shelves inside an opaque drying chamber. Heating of the crop is achieved by circulating air which is warmed during its flow through a low pressure drop thermosyphonic solar collector. Caramelization and localised heat damage do not occur since solar radiation is not directly incident on the crop or product. These

dryers are good for some perishables and fruits whose vitamin content is reduced considerably when exposed directly to sunlight. They are also good for colour retention in highly pigmented commodities which are adversely affected when exposed to direct sunlight.

These dryers tend to have higher operating temperatures than sun drying and direct dryers. They produce good quality products. However, fluctuations in temperatures of air leaving the air heaters, makes it difficult to maintain constant operating conditions within the drying chamber. Other shortcomings include operational difficulties of loading and unloading the trays and occasional stirring of the produce (Brace Research Institute, 1980). Brenndorfer et al. (1985), reported that distributed-type dryers have an inherent tendency towards greater efficiency since component units can be designed for optimal efficiency of their respective functions. Ekechukwu (1987), stated that these dryers are elaborate structures; requiring more capital investment in equipment and incur larger running (i.e. maintenance) costs than the integral units.

The major parts of a typical distributed natural-circulation solar-energy dryer are:

- an air-heating solar-energy collector;
- appropriately insulated ducting;
- a drying chamber; and
- a chimney.

In their study, Prakash and Kumar (2013), reported the study of an indirect solar maize dryer. The dryer assembly was made from hardboard. It consisted of a single-glazed passive solar air heater with a 1 m<sup>2</sup> single flat-plate absorber and an air gap of 5 cm from the glazing. The air heater was connected to an insulated drying chamber equipped with a chimney. 90 kg of wet maize was dried from a moisture content of 20 % wet basis to 12 % within 3 days on bright sunny days.

Clark (1981), Ibrahim and Hansen (1984), (Iyer, 1985), Micuta (1979), (Oostuizen, 1986) reported that performance studies have been done on other practically-realised designs of distributed-type natural-circulation solar dryers.

### **2.6.6 Mixed-mode natural-circulation solar-energy dryers**

The features of the integral (direct) type and the distributed (indirect) type natural-circulation solar-energy dryers are combined in this type of dryer. The necessary heat required for the dehydration process is furnished by the direct action of solar radiation incident on the product and the air which is pre-heated in a solar air heater. Typically, a mixed-mode natural-circulation solar-energy dryer has the same structural features as the distributed-type dryer (i.e. a solar air heater, a separate drying chamber and a chimney). Additionally, the walls of the drying chamber are glazed so that the solar radiation impinges directly on the product as in the integral-type dryers (Norton et al., 1987, Fleming et al., 1986, Fleming et al., 1987). Typical examples of practically-realised designs of the mixed-mode natural-circulation solar-energy dryers include the widely-reported solar rice dryers developed by Exell and Kornsakoo (1978) at the Asian Institute of Technology.

### **2.7 Active solar drying systems**

These systems only depend partially on solar-energy. They are distinct in that they use solar-energy and/or electrical or fossil-fuel based heating systems. Air circulation is facilitated by motorised fans and/or pumps. It should be noted that by application, all active dryers are forced convection dryers. However, a typical active solar dryer depends solely on solar-energy as the heat source but employs motorised fans and/or pumps for forced circulation of the drying air. A variety of active solar-energy dryers exist which could be classified into either the integral-type, distributed-type or mixed-mode dryers. In this study, active solar drying systems are not considered due to limitations by small-scale farmers in rural areas where grid electricity is not readily available and where the use of fans and pumps requires high initial capital injection.

### **2.8 Fundamentals of drying**

Drying implies moisture removal from a product. After growth of the crop ceases and a grain crop has reached physiological maturity, a considerable amount of moisture must still be removed from the grain before it can safely be stored (Loewer et al., 1994). Depending on the product, various methods and techniques are employed to dry a variety of different substances from solids to gases and even

liquids. Drying or dehydration is a continuous process with changes in moisture content, air and crop temperature and the humidity of air all occurring simultaneously.

### **2.8.1 The drying process**

Drying is a complex thermo physical and physiochemical process involving the thermodynamics of moist gases and moist solids (Gherzoi and Samochetev, 1960) and may be described as follows;

- 1) Heat and mass exchange between the surface of the substance and the surrounding medium, and
- 2) Transfer of heat and matter within the substance.

Husain (1972), indicates that the above definition of drying involves two fundamental and simultaneous processes which occur during drying. These are:

- 1) Mass transferred as liquid and/or vapour within the solid, and
- 2) Heat transferred to evaporate the surface moisture.

Heat transfer will occur as a result of convection, conduction, radiation, or a combination thereof. All three modes of heat transfer can occur during drying. However, the mode which is most overriding in most drying processes is the convective heat transfer (Kwendakwema, 1983).

Mass transfer within a drying product is dependent on two mechanisms which are:

- 1) The internal movement of moisture within the solid which is influenced by the internal physical nature of the solid and its moisture content.
- 2) The movement of water vapor from the material surface and this is affected by external conditions such as temperature, air humidity and flow rate and the exposed surface area (Gardner, 1971).

The rate of drying may be affected by either of the mechanisms, although they will both be proceeding simultaneously throughout the drying cycle. According to

Gardner (1971), the controlling mechanism depends on the material and stage of drying.

### **2.8.1.1 Internal conditions**

Due to heat transfer to a wet solid, a temperature gradient develops from the heated surface inward, while evaporation occurs at the surface. This results in migration of moisture from within the solid to the surface. The mechanism by which this may happen could be by diffusion, capillary flow and flow caused by internal pressures which result from shrinkage during drying. The net result of these phenomena occurring simultaneously at different stages of drying is moisture gradients through the material.

### **2.8.1.2 External conditions**

The mechanism of external evaporation at the solid surface and the effect of external variables, are of major importance in investigating the drying characteristics of a material and in choosing the correct type of dryer to employ and its operating conditions (Gardner, 1971). The external variables of paramount importance are temperature, humidity, rate and direction of air flow, the physical form of the solid, and method of supporting wet solids during the drying operation. The drying rate is affected by the properties of air and the properties of the solid (Desrosier and Desrosier, 1977). The most significant properties of the air are temperature, humidity and velocity, whereas, the significant characteristics of the solid are the type and variety of the solid, the free moisture content and the shape and size of the solid.

## **2.9 Drying kinetics**

The experimental determination of the drying characteristics of the wet solid is necessary in considering a drying problem so that a suitable type dryer can be selected and its sizing determined (Mujumdar and Menon, 1995) . According to Gardner (1971), a series of drying tests must be carried out under predetermined conditions which may be selected on an empirical basis. These may be influenced by what is already known about the material's sensitivity to temperature with the source of heat to be employed. Upon conducting these tests, the effects of various conditions of temperature, airflow, material subdivision and air humidity are studied to ascertain

optimum results. Under these conditions, the rates of drying are able to be determined.

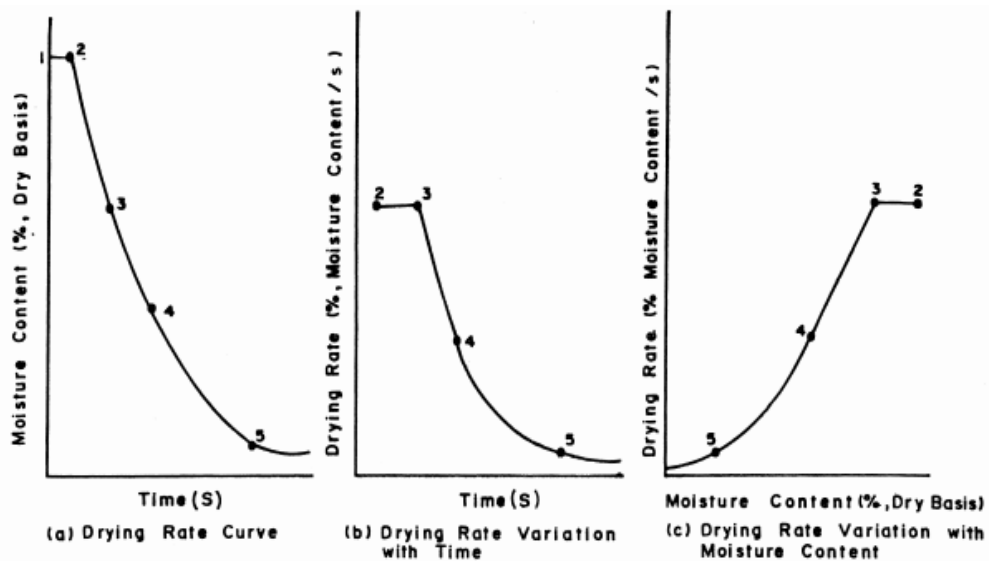
McCabe and Smith (1967), determined that generally, after a preliminary period, during which the temperature of the material adjusts itself to the drying conditions, the drying process can be divided into two distinct periods:

- 1) the constant-rate period, and
- 2) the falling rate drying period (Geankoplis, 2003) .

### 2.9.1 Constant drying rate period

This is the drying period during which the liquid vaporization rate remains constant per unit of drying surface.

Under the constant drying rate period, drying takes place from the surface of the product. It is simply the evaporation of moisture from the free-water surface. Figure 2.5 shows the various stages of drying.



**Figure 2.5: Schematic illustration of drying rate periods: 1-2 the heating period (constant moisture content); 2-3 the constant rate drying period; 3 the critical moisture content; 3-4 the first falling rate period; 4-5 the second falling rate period. Source: (Hall, 1980).**

The rate at which moisture is removed during this period mostly depends on the surrounding conditions and is only affected slightly by the nature of the product. This

period is when the product surface is saturated with moisture. Its temperature is fairly constant and approximately equal to the wet bulb temperature. The end of the constant drying rate period is marked by a decrease in the rate of moisture migration from within the product below that is sufficient to replenish the moisture being evaporated from the surface. This stage defines the critical moisture content, where environmental conditions cease to play a significant influence in the rate of drying. All drying takes place within the constant drying rate regime for non-hygroscopic materials.

The environmental factors such as the vapour pressure difference between the drying air and the wet surface, the surface area of the product exposed to the drying air, the mass transfer coefficient and the drying air velocity, are related to the drying rate (Hall, 1980, Henderson and Perry, 1955), according to equation 2.1:

$$\frac{dw}{dt} = \frac{K_m A_s}{R_o T} (P_v - P_{va}) = K_f \frac{A(T_a - T_s)}{L}. \quad (2.1)$$

The thermal conductance of the air film,  $K_f$ , is a function of the air velocity.

### 2.9.2 Falling drying rate period

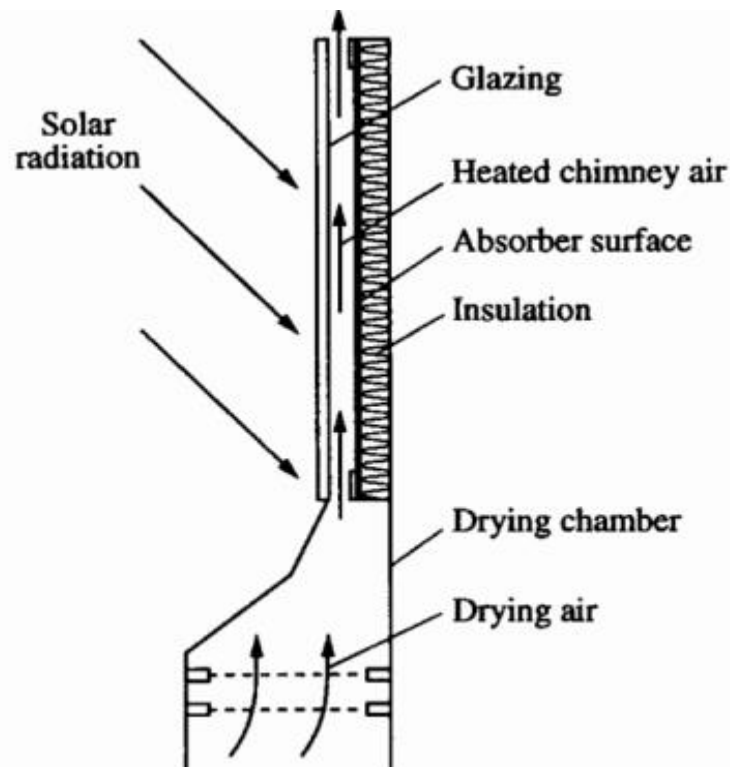
Hall (1980), stated that the critical moisture content of the product, which is the minimum moisture content at which the minimum rate of free moisture migration from within the product to the surface equals the maximum rate of moisture evaporation from the surface, is an equilibrium condition. The falling rate period is marked by the point below the critical moisture content. Figure 2.5 depicts this point accordingly. According to Hall (1980), the rate of drying in this period is dependent essentially on the rate of diffusion of moisture from within the product to the surface and also on moisture removal from the surface. He also points out that the period is usually subdivided into:

- 1) the first falling drying rate period which involves the unsaturated surface drying; and
- 2) the second falling drying rate period where the rate of moisture diffusion to the surface is slow and is the determining factor.

When it comes to agricultural products, the length of each of these drying periods is dependent upon the initial moisture content and the safe storage moisture content. It should be noted that for grains, the initial moisture content is usually below the critical moisture content, thus all drying takes place within the falling rate regime (Ekechukwu, 1999). It is worth noting that both the external factors and internal mechanisms controlling the drying processes in the two main rate regimes are important in determining the overall drying rate of products.

## 2.10 Solar chimney and estimation of buoyancy pressure

A solar chimney is a component in a passive solar drying system which serves the function of heating the air as a solar collector and helps in creating air flow. Solar chimneys vary in configurations. This is dependent on temperature rise, cost and prevailing climatic conditions among others. Figure 2.6 depicts a schematic of an existing design of a solar chimney for a solar crop dryer.



*Figure 2.6: Air heating flat-plate solar energy chimney. Source: (Ekechukwu and Norton, 1997).*

The design of a solar chimney characterised by an insulated vertical plate covered in glazing to form a flat-plate air heating collector. The solar radiation incident upon the glazing is converted to heat energy as it is absorbed by the chimney absorber plate. By convective heat transfer mechanism, the heat energy of the absorber plate is then lost to the air. This result in the air within the chimney channel to become less dense compared to the ambient air. The difference in density results into the buoyancy pressure air flow. Mathematically, the buoyancy pressure is given by equation 2.2 (Brenndorfer et al., 1985).

$$\Delta P_b = gH(\rho_{am} - \bar{\rho}_{ch}) \quad (2.2)$$

Where;  $\rho_{am}$  and  $\rho_{ch}$  are the densities of air in the ambient and air flowing in the chimney respectively in  $\text{kg/m}^3$ ,  $g$  is the acceleration due to gravity in  $\text{m/s}^2$  and  $H$  is the height of the chimney (m). In deriving equation 2.2, it was assumed that air density inside the chimney was uniform throughout the chimney length and that there is no leakage of air from the system except for the warm less dense air exiting at the outlet.

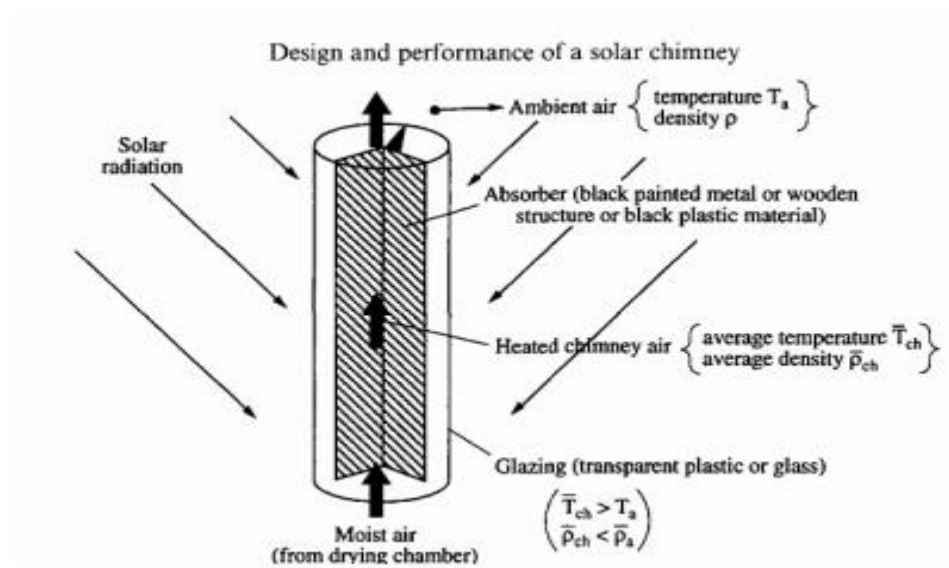
The height of a chimney helps to determine the temperature rise expected. Brenndorfer et al. (1985), showed in their work that with ambient air temperature of  $25^\circ\text{C}$  and 60 % relative humidity, a chimney height of only 2.45 m was sufficient to achieve a temperature rise of  $15^\circ\text{C}$  above ambient. This suggests that the height of the chimney has a profound role in determining the temperature rise in the chimney amongst other parameters (Cherotich, 2016).

Cherotich (2016), stated that besides the temperature rise attainable, cost per unit height of the chimney, compactness and accessibility of the air exit point are of importance in studies where taking of readings of temperature of air exiting the chimney and its velocity are concerned . He pointed out that accessibility of the air exit point is important for measurements of needed parameters.

Another design of the solar chimney is the greenhouse type. In this type of chimney, the glazing is a circular profile which receives solar radiation despite the incident angle. Figure 2.7 depicts the greenhouse type solar chimney. In comparison of the former and latter, the solar chimney designs for the same given surface area and

same test conditions, the greenhouse solar chimney attain a higher temperature because of its surface ability to receive the solar radiation no matter the angle of the incident radiation (Cherotich, 2016).

In terms of ease of design and construction, the flat plate solar chimney collector is preferable to the greenhouse type. The complexity also depends on the material used in making the chimney. Glass is rather difficult to work with for a circular design.



*Figure 2.7: Greenhouse solar chimney. Source: (Ekechukwu and Norton, 1997).*

## 2.11 Thin layer drying and mathematical modeling

Many studies have been reported on thin-layer drying of agricultural products and food materials (Akpinar et al., 2003, Agarry et al., 2014, Hossain and Bala, 2002). A considerable number of studies have been reported on the drying of cereals and fruits (Basunia and Abe, 2001). Agbossou et al. (2016), evaluated thin-layer drying characteristics of the grain maize in a mixed-mode forced convection solar dryer and determined the quality of maize for good germination, which is the big problem faced by the farmers. The objectives of their study were to investigate the effect of the drying time of maize grain on the solar tunnel in forced convection and to compare drying behaviour at the different positions in the dryer. Different

mathematical models were used. In the current study, mathematical models are determined under natural convection conditions.

### 2.11.1 Mathematical modeling of solar drying curves

The moisture ratio of samples during drying can be expressed by the following equation 2.3:

$$X_R = \frac{X_t - X_e}{X_o - X_e} \quad (2.3)$$

Where  $X_R$  is the dimensionless moisture content ratio;  $X_t$ ,  $X_e$  and  $X_o$  are the moisture content at any given time, the initial moisture content and the equilibrium moisture content, respectively.

Some mathematical models to which drying curves will be fitted to experimental data are given in the Table 1, (Agbossou et al., 2016).

**Table 1. Mathematical models given by various authors for the solar drying curves**

Model No.	Model equations	Model Name
1	$\frac{X_t}{X_o} = \exp(-kt)$	Newton
2	$\frac{X_t}{X_o} = \exp(-kt^n)$	Page
3	$\frac{X_t}{X_o} = a * \exp(-kt)$	Henderson and Pabis
4	$\frac{X_t}{X_o} = a * \exp(-kt) + c$	Logarithmic
5	$\frac{X_t}{X_o} = a * \exp(-k_1t) + b * \exp(-k_2t)$	Two-Term
6	$\frac{X_t}{X_o} = 1 + at + bt^2$	Wang and Singh
7	$\frac{X_t}{X_o} = a * \exp(-kt) + (1 - a)\exp(-kat)$	Two-Term Exponential
8	$\frac{X_t}{X_o} = \exp[-(kt)^n]$	Modified Page
9	$\frac{X_t}{X_o} = a * \exp(-kt) + (1 - a)\exp(-gt)$	Verma et al.
10	$\frac{X_t}{X_o} = a * \exp(-kt) + (1 - a)\exp(-kbt)$	Yaldiz and Ertekin
11	$\frac{X_t}{X_o} = \exp(-k \left(\frac{t}{\tau}\right)^n)$	Modified Page Equation
12	$\frac{X_t}{X_o} = 1 + at + bt^2 + ct^3$	Gökhan GÜRLEK
13	$\frac{X_t}{X_o} = a * \exp(-kt^n) + bt$	Midilli et al.
14	$\frac{X_t}{X_o} = a * \exp(-kt) + b * \exp(-gt) + c * \exp(-ht)$	Modified Henderson and Pabis

Madamba et al. (1996) and Midilli et al. (2002) stated that the mathematical models scope from; theoretical, semi-empirical and pure empirical. Theoretical models cater

for only the internal resistance to moisture transfer while the semi-empirical and purely empirical models take into account the external resistance to moisture transfer to the air. Agbossou et al. (2016), employed the theoretical model based on Fick's law considering the geometric shape of a sphere, ignoring the grain volumetric variation and considering the known moisture condition at the grain surface.

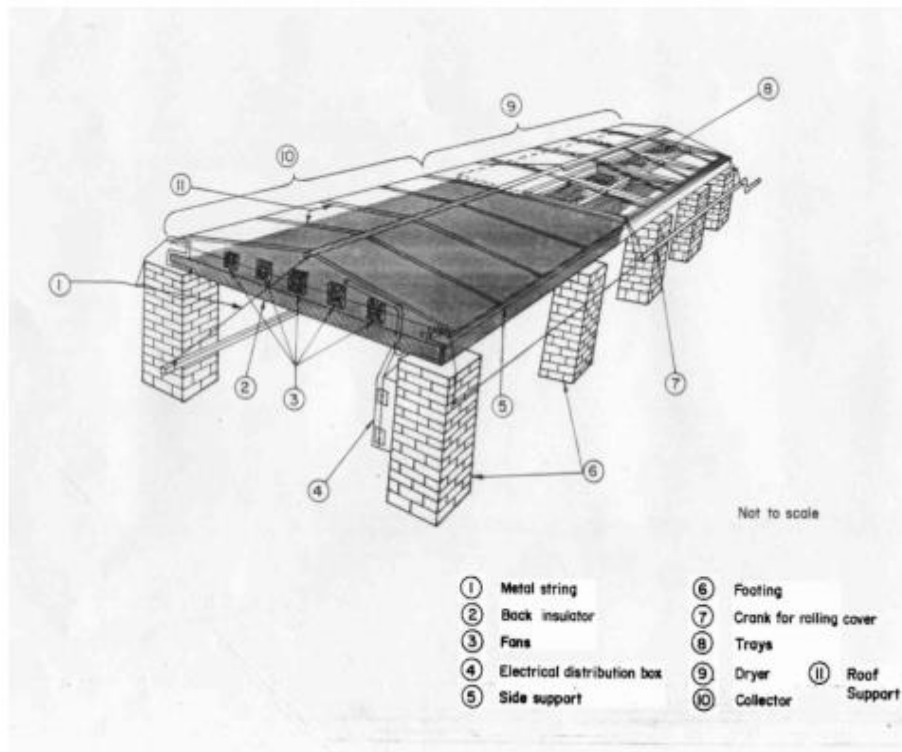
## **2.12 Solar tunnel dryer**

This dryer was originally developed at the University of Hohenheim, Germany in the early eighties for small scale production of dried fruits, vegetables, spices, fish etc... (Esper et al., 1994). The solar tunnel dryer is widely used for drying various agricultural products. The dryer consists of different parts such as drying chamber, collector area and chimney. A solar tunnel dryer is a tunnel like framed structure covered with Ultra-violet (UV) stabilized polythene sheet, where agricultural and industrial products could be dried under the drying chamber. The product to be dried is placed in the tunnel dryer drying chamber.

In forced convection solar tunnel dryers' air at the required flow rate is provided by a DC operated fan powered by a battery. For natural convection solar tunnel dryers, air movement is dependent on buoyancy pressure created in the chimney section. In order to prevent rain water from entering the dryer, the cover is fixed like a sloping rod or semi cylindrical shape. The solar radiation passes through the transparent glazing of the dryer. Heat is transferred from the absorber to the air in the collector and heated air from the collector passes over the product in the drying chamber absorbing the moisture from the product. Solar radiation also impinges directly on the product being dried in the drying chamber section.

The performance of a solar tunnel dryer is dependent on the weather conditions (Piyush et al., 2016) . To get a better output the day should be clear and sunny so that the maximum beam radiation incident on the dryer can be utilised. This dryer is very useful to small scale farmers and household farmers for drying agricultural products which can be prevented from going to waste due to rain, dust and insects as the material being dried is covered. Parameters which affect performance of a solar tunnel dryer include: absorptivity of the collector, transmissivity of the covering polythene sheet, air flow velocity, drying layer thickness and relative humidity of the air.

Figure 2.8 shows a forced convection Solar Tunnel Dryer.



**Figure 2.8: The AIT Solar Tunnel Dryer. Source: (Mastekbayeva et al., 1998).**

In their design work on fabrication and performance analysis of solar tunnel dryers using various absorber materials, a total drying time of 20 hours was required for the solar tunnel dryer to reduce the moisture content of maize grains from an initial value of 37 per cent (w.b.) to a final moisture content of 13 per cent (w.b.) while the open sun drying required on an average 72 drying hours to obtain the same level of moisture content which resulted in net saving in drying time of 72.22 per cent for solar tunnel dryer over open- sun drying (Piyush et al., 2016).

In a forced convection Solar Tunnel Dryer developed by Schirmer et al. (1996) to dry bananas, the results of the experiments indicated the varied collector temperatures of between 40 °C and 65 °C with global solar radiation of up to 1000 W/ m<sup>2</sup> respectively . The bananas which had an initial moisture content of 69 % (w.b.) were dried to a final moisture content of 30 % (w.b.) in 2-3 days under these conditions. Despite the dryer significantly reducing the moisture content, the drying time was

highly dependent on the weather conditions and more so on the amount of solar insolation registered.

Investigations in the drying of chilli using a forced convection mixed- mode Solar Tunnel Dryer, gave a reduction in drying time by over 10 hours as compared to open-sun drying (OSD), (Hossain and Bala, 2002). It was found that the moisture content of the chilli was reduced from 2.85 to 0.05 kg kg<sup>-1</sup> (d.b.) in 20 hours while OSD took 32 hours to bring down the moisture content to 0.4 kg kg<sup>-1</sup> (d.b.). Solar Tunnel Dryers (STD) therefore reduces the drying time.

The configuration of most solar tunnel dryers is such that the collector is connected to the drying chamber directly. This simplifies their construction and reduces the cost. Among the many existing dryers, Solar Tunnel Dryers provide a good option for developing countries with low incomes accompanied with shortage of skilled personnel.

### 2.13 Basic design equations of a solar dryer

In order to come up with parameters of the dryer, some of the factors considered were the amount of water to be removed from the product to be dried given by equation 2.4:

$$m_w = m_p (M_i - M_f) / (100 - M_f) \quad (2.4)$$

The final relative humidity or equilibrium relative humidity is calculated using equation 2.5:

$$ERH = 1 - \exp (-k (t+C)Me^N) \quad (2.5)$$

The water activity is calculated using equation 2.6:

$$a_w = ERH/100 \quad (2.6)$$

The quantity of heat required to remove the water is given by equation 2.7 :

$$Q = m_w * h_{fg} \quad (2.7)$$

Latent heat of vapourisation is calculated using equation 2.8:

$$h_{fg}^* = h_{fg} [1+a * \exp (bM)] \quad (2.8)$$

Total heat energy required to evaporate water is determined using equation 2.9:

$$E = \dot{m} (h_f - h_i) t_d \quad (2.9)$$

The average drying rate is calculated using equation 2.10:

$$m_{dr} = m_w/t_d \quad (2.10)$$

To determine the mass of dry air needed for drying, equation 2.11 is employed:

$$\dot{m} = m_{dr} / (w_f - w_i) \quad (2.11)$$

Determination of the collector area is solved by use of equation 2.12:

$$AcI\eta = E = \dot{m} (h_f - h_i) t_d \quad (2.12)$$

This equation is simplified to a simple form which is equation 2.13:

$$Ac = E/I\eta \quad (2.13)$$

Volumetric airflow rate is given by equation 2.14:

$$Va = m_a/\rho_a \quad (2.14)$$

#### **2.14 Mycotoxin contamination of maize grains**

Maize is prone to fungal infection during the pre- and post-harvest period (Janardhana et al., 1999). Major mycotoxins that can occur in cereal grains and cereal-based products are Fusarium mycotoxins deoxynivalenol (DON), (occurring mainly in wheat, maize, barley, oats, rye), T-2 and HT-2 toxins (oats, wheat, barley), zearalenone (maize, wheat) and fumonisins (maize) and Aspergillus or Penicillium mycotoxins, Aflatoxins (maize) and Achratoxin A (maize, wheat, barley, rye). Human or animal exposure to these natural contaminants can lead to acute or chronic diseases, and in some cases death.

In this study experiments were conducted to determine levels of Aflatoxins in maize obtained straight from the field, maize dried on open on a sheet placed on the ground and maize dried in a Solar Tunnel Dryer.

The method of determination of Aflatoxins was the Lateral Flow Immunoassay (LFA) among the many methods available.

## **2.15 Closing remarks**

This Chapter described what postharvest losses in maize constitute, the significance of Open Sun Drying as well as the purposes of drying. Comparisons between Open Sun Drying and solar drying have been outlined. Further, types of dryers and classification of solar energy drying systems are presented so that an understanding of artificial dryers can be appreciated. The kinetics of drying and the description of different types of solar chimneys are given. The Chapter also introduces the Solar Tunnel Dryer and some basic design equations. Thin layer drying and mathematical modelling is discussed as well as the determination of the presence of Aflatoxins in maize.

The next Chapter deals with the Design and Construction of the Solar Tunnel Dryer.

## CHAPTER III

### 3.0 DESIGN AND CONSTRUCTION OF THE SOLAR TUNNEL DRYER

This Chapter presents the design considerations for the Solar Tunnel Dryer. A description of how the dryer was arrived at is also given. The conditions and assumptions used in designing the Solar Tunnel Dryer and the design calculations are also presented.

#### 3.1 Design considerations for the solar tunnel dryer

The following factors were considered in the design of the natural convection Solar Tunnel Dryer system:

- 1) The amount of moisture to be removed from a given quantity of wet maize;
- 2) Harvesting period during which the drying is needed (i.e. whether harvest time coincides with the dry or wet season);
- 3) The daily sunshine hours for the selection of the total drying time,
- 4) The quantity of air needed for drying;
- 5) Daily solar radiation to determine energy received by the dryer per day;
- 6) Wind speed for the calculation of air vent dimensions.

##### 3.1.1 Design conditions and assumptions for construction of the solar tunnel dryer

Table 2 presents the conditions and assumptions considered for the dryer design.

**Table 2: Conditions and assumptions for construction of dryer**

Items	Condition or assumption
Location	UNZA (Latitude 15.3°S and Longitude 28.3°E)
Crop	Maize

Drying period	Mid-March- to May
Drying per batch (3 days /batch)	
Loading rate (mp)	134 kg
Initial moisture content (M <sub>i</sub> ) w.b (moisture content at harvest)	30 %
Final moisture content (M <sub>f</sub> ) w.b (moisture content for storage)	12.5%
Ambient air temperature (T <sub>am</sub> )	21 °C
Ambient relative humidity (RH <sub>am</sub> )	59 %
Maximum allowable temperature (T <sub>max</sub> )	65 °C
Drying time Sunshine hours), td	7 hrs * 3 days
Incident solar radiation, I	19.99 MJ/m <sup>2</sup> /day
Collector efficiency, η	30 %
Wind speed,	2.06 m/s

### 3.1.2 Design description of the solar tunnel dryer

The dryer size was predetermined to be a smaller version of the Hohenheim Solar Tunnel Dryer with a semi cylindrical cross- section (Mastekbayeva et al., 1998). Its dimensions were length (L) 5m and width (W) 2m. These dimensions were arrived at after careful examination of the design conditions and assumptions. The drying temperature was established as a function of the maximum limit of temperature the maize crop could withstand depending on later usage.

### 3.1.3 Design calculations for the solar tunnel dryer

1. The amount of moisture to be removed from the maize, m<sub>w</sub>, in kg was calculated using the following equation 2.4:

$$m_w = m_p(M_i - M_f) / (100 - M_f) \quad (2.4)$$

where: m<sub>p</sub> is the initial mass of the product to be dried, kg; M<sub>i</sub> is the initial moisture content, % wet basis and M<sub>f</sub> is the final moisture content, % wet basis.

Therefore,

$$m_w = 134 \text{ kg} * (30 - 12.5) / (100 - 12.5)$$
$$= \underline{\mathbf{26.8 \text{ kg}}}$$

2. Final relative humidity or equilibrium relative humidity was calculated using sorption isotherm for shelled corn given by Modified Henderson (ASAE, 2000), equation 2.5:

$$ERH = 1 - \exp(-k(t+C)M_e^N) \quad (2.5)$$

Where:  $k = 6.6612 * 10^{-5}$

$$N = 1.9677$$

$$C = 42.143$$

Therefore,

$$ERH = 1 - \exp(-6.6612 * 10^{-5}(40 + 42.143)14.29^{1.9677})$$
$$= 0.6413 * 100 \%$$
$$= \underline{\mathbf{64.13 \%}}$$

3. Water activity is given by equation 2.6:

$$a_w = ERH/100 \quad (2.6)$$

Therefore,

$$A_w = 64.13/100$$
$$= \underline{\mathbf{0.6413}}$$

4. The quantity of heat needed to evaporate the water was calculated using the following equation 2.7:

$$Q = m_w * h_{fg} \quad (2.7)$$

Where:

Q is the amount of energy required for the drying process, kJ

$m_w$  is the mass of water, kg

$h_{fg}$  is latent heat of evaporation, kJ/kg H<sub>2</sub>O

The amount needed is a function of temperature and moisture content of the crop. The latent heat of vaporization was calculated using an equation given by Youcef-Ali et al. (2001) as follows :

$$h_{fg} = 2,260 \text{ kJ/kg}$$

$$h_{fg}^* = h_{fg} [1 + a \cdot \exp(bM)] \quad (2.8)$$

$$= 2,260 [1 + 2.1 \exp(-170 \cdot 0.1429)]$$

$$= 2,678.12 \text{ kJ}$$

Therefore,

$$Q = 26.8 \cdot 2,678.12$$

$$= \underline{\underline{77,773.62 \text{ kJ}}}$$

The amount of heat needed is a function of temperature and moisture content of the crop.

5. Total heat energy E (kJ) required to evaporate water was calculated as follows:

$$E = \dot{m} (h_f - h_i) t_d \quad (2.9)$$

Where;

E = total heat energy, kJ

$\dot{m}$  = mass flow rate of air, kg/hr

$h_f$  and  $h_i$  = final and initial enthalpy of drying and ambient respectively, kJ/kg dry air

$t_d$  = drying time, hr

From the psychrometric chart,

$$h_i = 49.5 \text{ kJ / kg of dry air}$$

$$h_f = 69 \text{ kJ / kg of dry air}$$

$$w_i = 0.011 \text{ kg of water / kg of dry air, initial humidity ratio}$$

$$w_f = 0.0168 \text{ kg of water / kg of dry air, final humidity ratio}$$

6. Average drying rate,  $m_{dr}$ , was determined from the mass of moisture to be removed by solar heat and drying by the following equation 2.10:

$$m_{dr} = m_w / t_d \quad (2.10)$$

Where,

$$m_w = 26.8 \text{ kg water and } t_d = 21 \text{ hr}$$

$$= 26.8 / 21$$

$$= \underline{\underline{1.276 \text{ kg / hr}}}$$

7. Mass of air needed for drying was calculated using the equation given by Sodha et al. (1987) as follows ;

$$\dot{m} = m_{dr} / [w_f - w_i] \quad (2.11)$$

$$= 1.276 \text{ kg H}_2\text{O /hr} / [0.0168 - 0.011] \text{ kg H}_2\text{O / kg dry air}$$

$$= \underline{\underline{220.03 \text{ kg dry air / hr}}}$$

8. From the total useful heat energy required to evaporate moisture and the net radiation received by the dryer collector, the solar drying system collector area  $A_c$ , in  $m^2$  can be calculated from the following equation:

$$A_c I \eta = E = \dot{m} (h_f - h_i) t_d \quad (2.12)$$

Therefore, the area of the collector is:

$$A_c = E / I \eta \quad (2.13)$$

Where E is the total useful energy received by the drying air, kJ; I is the total global radiation on the horizontal surface during the drying period, kJ/ m<sup>2</sup> and η is the collector efficiency, (Sodha et al., 1987).

$$\begin{aligned} E &= 220.03 \text{ kg dry air / hr (69-49.5) kJ / kg dry air * 21 hr} \\ &= 90,102.29 \text{ kJ} \\ &= \underline{\underline{90.102 \text{ MJ}}} \end{aligned}$$

$$I = 19.99 \text{ MJ/m}^2/\text{day}$$

$$\eta = 30 \% \text{ (taking efficiency as 30 \% (Sodha et al., 1987))}$$

$$\begin{aligned} I \eta &= 19.99 \text{ MJ / m}^2/\text{day} * 30 / 100 * 3 \text{ days} \\ &= \underline{\underline{17.991 \text{ MJ/m}^2}} \end{aligned}$$

Therefore,

$$\begin{aligned} A_c &= 90.102 / 17.991 \\ &= \underline{\underline{5.01 \text{ m}^2}} \end{aligned}$$

9. Volumetric airflow rate, V<sub>a</sub> is obtained by dividing m<sub>a</sub> by density of air which is 1.2 kg/m<sup>3</sup>

$$V_a = m_a / \rho_a \quad (2.14)$$

Therefore;

$$\begin{aligned} V_a &= 220.03 / 1.2 \\ &= \underline{\underline{183.36 \text{ m}^3/\text{hr}}} \end{aligned}$$

### **3.1.4 Construction of the solar tunnel dryer**

Upon approval of the design drawings (drawings shown in Appendix II\_ VII) the materials for making the dryer were bought. Basically, the materials included shutter ply boards, planks, iron sheets; UV stabilized plastic, wood glue and nails. A detailed list of the materials is shown in Appendix VIII. The dryer was made at the Technology Development and Advisory Unit (TDAU), University of Zambia. Figures 3.1, 3.2 and 3.3 present the front view, side view and end view of the constructed dryer respectively.



*Figure 3.1: Front view of the solar tunnel dryer.*



*Figure 3.2: Side view of the solar tunnel dryer.*



*Figure 3.3: End view of the solar tunnel dryer.*

### **3.1.5 Description of the solar tunnel dryer and its components**

The major components of the Solar Tunnel Dryer are solar collector, drying chamber and the covered flat- plate solar chimney. Details for each unit are given in the following sections:

#### **3.1.5.1 The collector unit**

The collector unit was a flat- plate type covered with (ultraviolet) UV stabilized plastic. The airflow was meant to flow above the absorber of the solar collector. Brenndorfer et al. (1985) and Ekechukwu and Norton (1999b) reported that this type of solar collector registers low thermal losses . The absorber plate was made from a shutter ply board of length (L) 2.5 m and width (W) 2 m. The surface was painted black to increase absorptivity of solar insolation. Figure 3.4 shows the collector unit painted black.



*Figure 3.4: The open dryer showing the solar absorber painted black and the drying tray.*

### **3.1.5.2 The drying unit**

The drying unit had a base plate made from shutter ply board just as the sides. It was covered with UV stabilized plastic. The dimensions were the same as for the collector unit. Figure 3.4 shows the drying unit with the drying tray in place.

### **3.1.5.3 The chimney unit**

At the end of the drying unit, a vertical solar chimney made of a covered flat plate collector was attached. The cover for the chimney collector was overlapping with the cover for the drying unit. Figure 3.4 shows the chimney set up. The chimney was made from shutter ply boards and a flat sheet of galvanized iron painted black was inserted for enhanced solar radiation absorption. The whole front part was covered with UV stabilized plastic.

The dryer was made in three subunits due to its size. Two stands with legs of 60 cm were used for the dryer platform. Assembling of the dryer was done at the experimental site after transporting the individual units.

## **3.2 Mode of operation of the dryer**

Solar Tunnel Dryers utilize the energy of the sun and wind to dry agricultural products. As the dryer is a natural convection type, a unidirectional air flow is assumed. The product to be dried is placed in a thin layer/single layer in the drying unit. Solar radiation (SR) passes through the transparent cover of the collector. Heat is transferred from the absorber to the air in the collector through convective transfer mechanism. The heated air becomes less dense compared to ambient air and as a result, buoyancy pressure is generated due to the density differences between the air inside the dryer and ambient air.

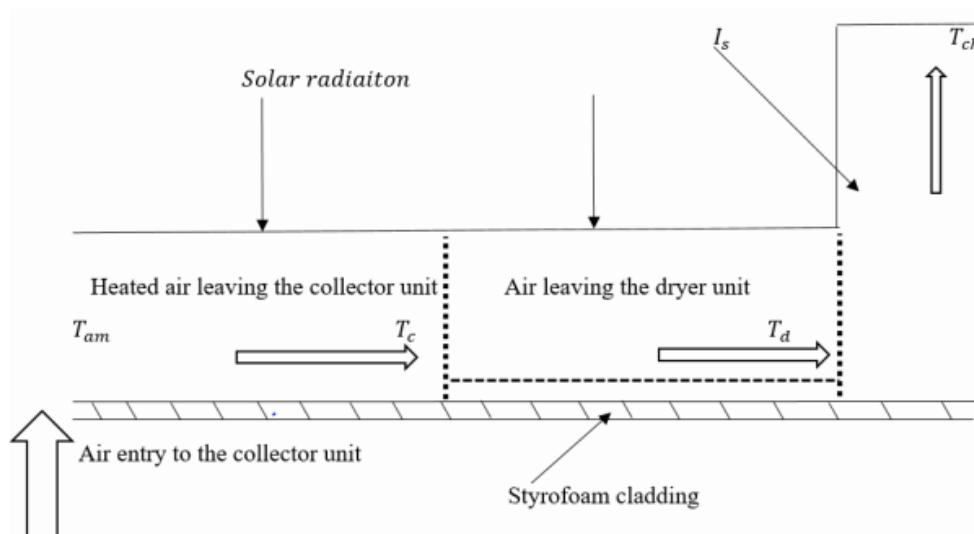
The effect of buoyancy pressure in conjunction with the wind force causes the air in the collector unit to be displaced to the drying unit. If the product is loaded, mass and heat transfer between the product and the air occurs. Depending on the moisture content of the product being dried, the air temperature is expected to reduce while the relative humidity increases. The heat and mass transfer process which occurs simultaneously causes the product to dry with time. Apart from moisture evaporation taking place due to heated air from the collector, SR also impinges directly on the

product being dried since the cover for the drying unit is also transparent. It is worth noting that the product is dried through convective heat transfer and direct heating and these results in high drying rates for the Solar Tunnel Dryer.

When there is no product in the drying unit, the air from the collector unit continues to be heated as it passes through the drying unit and therefore becomes hotter than the air at the collector unit. However, this phenomenon is also observed if the moisture content of the product being dried is low.

As the air exiting the drying unit passes through the chimney, further heating takes place and causes the air to rise by natural convection to the outside of the dryer through the exit provided at the back of the chimney. For as long as there is solar radiation, this cycle of air movement continues.

Figure 3.5 shows a schematic way of how the air flow occurs in a Solar Tunnel Dryer. The experimental dryer did not have any form of insulation as wood is a bad conductor of heat.



*Figure 3.5: Air flow in the solar tunnel dryer. Source: (Cherotich, 2016).*

### 3.3 Closing remarks

In this Chapter, all aspects concerning the design, construction and operation of the Solar Tunnel Dryer have been given. The next Chapter deals with the Methodology.

## CHAPTER IV

### 4.0 METHODOLOGY

This Chapter describes the procedures of what was done to conduct the experiments as well as the instruments used. As alluded to in the previous Chapter, a Solar Tunnel Dryer with a semi cylindrical shape was designed and constructed for the purpose of conducting experiments. Being a natural convection dryer, an air guide was made to allow for streamlined airflow (Cherotich, 2016) .

The maize cobs for the experiments were grown at the University of Zambia, School of Agriculture Sciences Field Station. Figure 4.1 depicts the crop when it had almost reached physiological maturity.



*Figure 4.1: Maize crop. University of Zambia, Lusaka (2017).*

### 4.1 Experimental site and procedures

The experiments were conducted at the Department of Agricultural Engineering field station at the University Zambia. The coordinates of the area are: Latitude 15.3°S; Longitude 28.3°E. The dryer was positioned in a north- south orientation. A total number of three (03) experiments were carried out. Before each experiment, the

initial moisture content was determined. Experiments were carried out between 09:00 and 16:00 hours each day until a moisture of 12.5% was reached.

The Solar Tunnel Dryer was positioned on a flat ground on its platform. To take the readings of air temperature, relative humidity and solar radiation, a multi probe Campbell Scientific Inc data logger (Kadam1 et al.) (model: CR 1000) was connected to the Solar Tunnel Dryer.

The data logger recorded the air temperatures through three (03) thermocouple type temperature probes (Campbell Scientific, Model T108, accuracy  $\pm 0.2$  °C). These temperature probes are capable of recording temperature ranging between -5 and +95 °C. Figure 4.2 depicts the data logger with probes extending outside.



***Figure 4.2: Pictorial view of data logger connected to laptop and probes extending out.***

The data logger and laptop were set up in a room whereas the probes were inserted in the dryer.

Recordings of relative humidity were done using a relative humidity probe (Model HMP60-L, accuracy  $\pm 0.2\%$ ) that was capable of measuring temperature and humidity ranges of -40 °C to 60 °C and 0 and 100 %, respectively.

A pyranometer (Kipp and Zonen, Model CM11, accuracy  $\pm 0.5 \text{ W/m}^2$ ) placed on a flat horizontal block surface near the Solar Tunnel Dryer, and used to measure the solar insolation. For measurement of air velocities, a digital air flow meter (Model TES 1340, accuracy  $\pm 0.1 \text{ m/s}$ ) was used for air velocities between 0 and  $30 \text{ m s}^{-1}$ . Figure 4.3 shows a pyranometer placed on a flat block which was near the dryer.



**Figure 4.3:** *Pictorial view of pyranometer.*

Figure 4.4 is showing cables of the probes for temperature, relative humidity and the pyranometer extending out to the dryer.



**Figure 4.4:** *Pictorial view of cables extending to the dryer.*

Figure 4.5 is depicting a temperature probe measuring air temperature at collector exit.



***Figure 4.5: Pictorial view of probe measuring air temperature at collector exit.***

Figure 4.6 shows a probe measuring air temperature of air exiting the dryer section into the chimney.



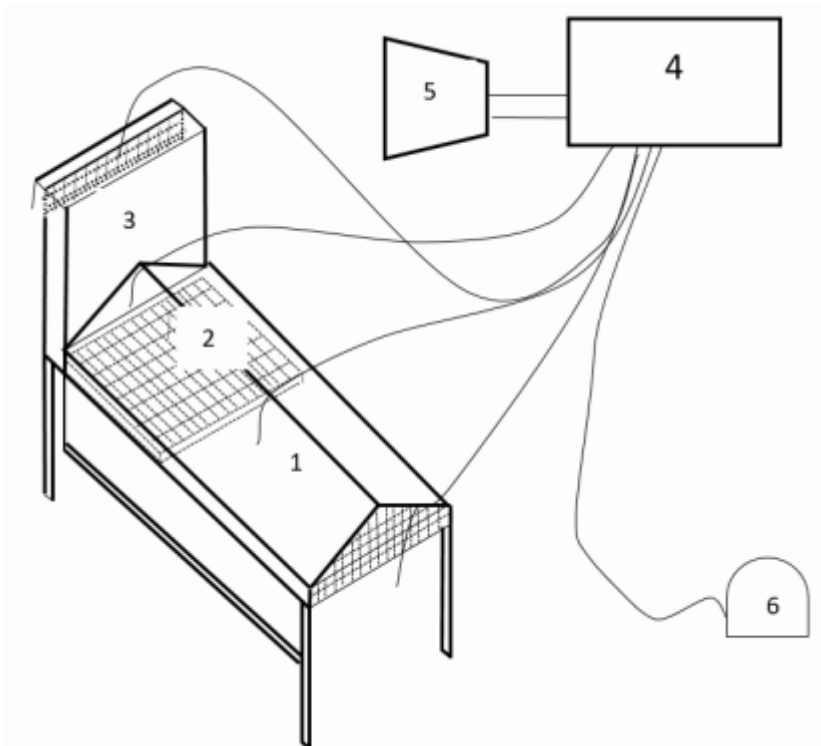
***Figure 4.6: Pictorial view of probe measuring air temperature at dryer exit.***

Figure 4.7 depicts the probe measuring the temperature of air exiting the chimney.



*Figure 4.7 Pictorial view of probe measuring air temperature at chimney exit.*

The overall setup is given in Figure 4.8



*Figure 4.8: Experimental set-up of the solar tunnel dryer and the equipment: collector unit, drying unit, bare flat- plate chimney Unit, Data logger, Computer and solar pyranometer. Source: (Cherotich, 2016).*

#### 4.2 Determination of the initial moisture content of maize cobs

The oven method was used to measure the moisture content of the grain before each set of experiment. A few cobs to fit in the oven drier (Jeio Tech, Model ON-02G, accuracy,  $\pm 0.5\%$ ) were selected randomly and their weight measured. The cobs were then placed in the convection oven set at a temperature of  $103^{\circ}\text{C}$  for 72 hours to remove completely all the moisture (Loewer et al., 1994).

The moisture content of grain was expressed as the percentage of total weight of the sample that is water. Equation 4.1 expresses the relationship

$$\text{MC}_{\text{wb}} = W_w * 100 / W_t \quad (4.1)$$

Where,

$\text{MC}_{\text{wb}}$  = percent moisture content on a wet basis

$W_t$  =  $W_w + W_{\text{dm}}$

= total sample weight

Initial moisture content  $M_o$  on wet basis can also be calculated by equation 4.2:

$$M_o = \frac{(W_1 - W_2)}{W_1} \times 100 \quad (4.2)$$

Where,

$W_1$  is total weight of sample and  $W_2$  is final weight of sample.

#### 4.3 Maize drying experiments

Having determined the initial moisture content, 134 kg of maize which was partially field-dried was placed in the dryer. A control experiment using Open-Sun Drying was set up adjacent to the Solar Tunnel Dryer. Nine cobs were selected from the dryer and the control setup, for hourly or every second hour moisture weight loss measurements. The cobs were arranged in such a way that three cobs were placed in

the front position, middle and end position according to the width and length of the dryer. Other cobs were placed on the plastic where the maize was dried on open ground.

The experiments were conducted from 09:00 hours to 16:00 hours. At the end of the experimental day, the maize samples that were used for checking weight loss were placed in airtight plastics to prevent moisture ingress or egress on the cobs.

From the weight loss measurements, the moisture content was calculated using equation 4.3:

$$M = 100 - \left( \frac{W_1(100 - M_o)}{W_2} \right) \quad (4.3)$$

Figures 4.9 and 4.10, depicts the maize being dried in the dryer and on the polythene black sheet on open ground.



***Figure 4.9: Maize being dried in the solar tunnel dryer (STD).***



*Figure 4.10: Open-Sun drying experiment (control).*

#### **4.4 Determination of Aflatoxins**

In this study, it was desired to determine levels of Aflatoxins in the maize crop. As alluded to earlier in the text, some cobs were weighed every one or two hours to determine weight loss. These cobs are the ones from which maize grains were obtained to prepare flour that was used in the Lateral Flow Immunoassay (LFA). Maize flour was also prepared from maize which was harvested and stored directly in the workshop. Below are the steps under taken to test for Aflatoxins in the nine samples of maize flour that was prepared.

- 5 g of ground maize (flour) was weighed
- 30 ml of 65 % ethanol was added
- Samples were shaken for three minutes using a shaking machine
- The mixture was filtered through Whatman No.1 filter paper
- 500  $\mu\text{L}$  of sample buffer solution was pipetted into sample dilution cups
- 100  $\mu\text{L}$  of the filtrate was added to the same dilution cups and thoroughly mixed
- 100  $\mu\text{L}$  of the mixture was pipetted into the measuring cups
- Aflatoxin strips were inserted into the measuring cups

- The inserted strips were allowed to stand for six minutes and reading of Aflatoxins content was done using a micro Reader

#### 4.5 Mathematical modeling of solar drying curves

The moisture ratio of samples during drying can be calculated using equation 2.3:

$$X_R = \frac{X_t - X_e}{X_o - X_e} \quad (2.3)$$

Where  $X_R$  is the dimensionless moisture content ratio;  $X_t$ ,  $X_o$  and  $X_e$  are the moisture content at any given time, initial moisture content and the equilibrium moisture content, respectively.

By use of the regression analysis, the drying curves were fitted to the experimental data using the fourteen mathematical models given in Table 1. However, the moisture ratio  $X_R$  was simplified to  $X/X_o$  instead of  $(X-X_e)/(X_o-X_e)$ , due to continuous fluctuation of relative humidity of the drying air in the dryer (Diamante and Munro, 1993) and (Goyal et al., 2007).

#### 4.6 The chimney unit buoyancy pressure head

The solar chimney collector was evaluated to determine the buoyancy pressure head developed. Brenndorfer et al. (1985), stated that the buoyancy pressure head, generated by the chimney, can be calculated according to equation 2.2:

$$\Delta P_b = gH(\rho_{am} - \bar{\rho}_{ch}) \quad (2.2)$$

Where;  $\Delta P_b$  is the chimney buoyancy pressure head in  $N\ m^{-2}$ ,  $g$  is the acceleration due to gravity in  $m\ s^{-2}$ ,  $H$  is the chimney height in  $m$ ,  $\rho_{am}$  is the ambient air density in  $kg\ m^{-3}$  and  $\bar{\rho}_{ch}$  is the mean chimney air density in  $kg\ m^{-3}$ .

Ekechukwu and Norton (1997), reported that for air temperatures between 25 and 90 °C, equation 2.2 was manipulated to yield equation 4.5 which uses the air temperatures as opposed to equation 2.2 which uses air density to calculate buoyancy pressure.

$$\Delta P_b = 0.00308gH(T_{ch} - T_{am}) \quad (4.5)$$

By the use of equation 4.5, the buoyancy pressure head was obtained using the temperature of the air leaving the chimney unit and ambient air temperature defined earlier as  $T_{ch}$  and  $T_{am}$  respectively.

#### **4.7 Closing remarks**

The Chapter has outlined in detail the steps undertaken to carry out the experiments in order to achieve specific results. The next Chapter presents the results obtained.

## CHAPTER V

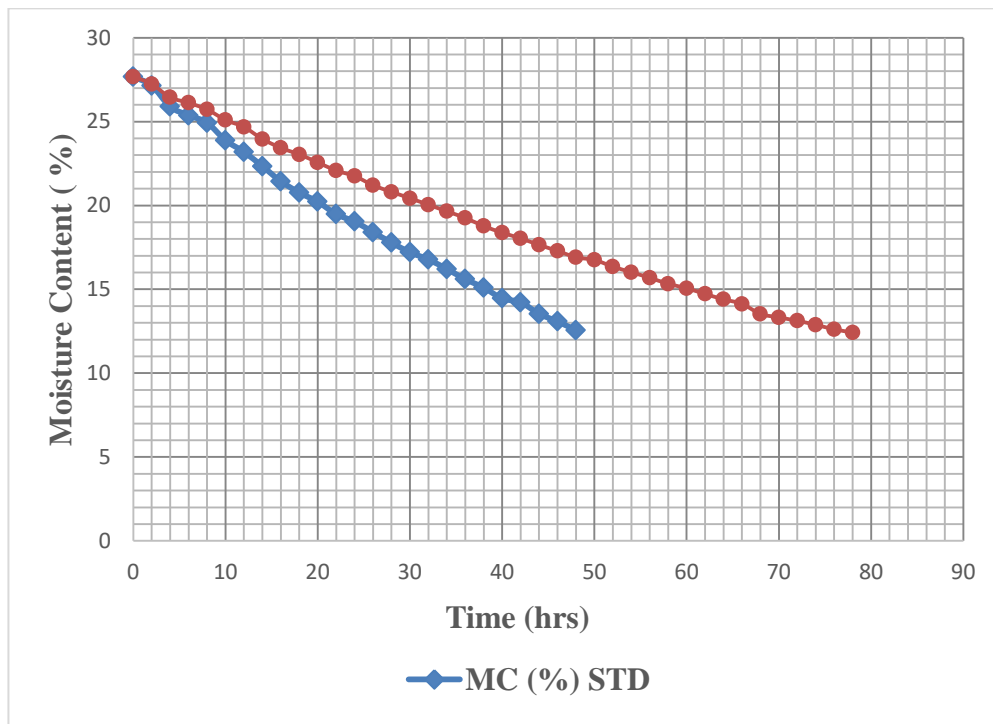
### 5.0 EXPERIMENTATION AND RESULTS

This Chapter presents the results of the different experiments carried out in this study

The results for the comparison of time taken to dry maize in a Solar Tunnel Dryer (STD) versus Open- Sun Drying (OSD); Aflatoxins levels in maize dried in a STD, OSD and that taken Straight From the Field (SFF); appropriate mathematical thin layer model for predicting the drying of maize; performance of the solar-collector chimney on the natural convection dryer, are given below.

#### 5.1 Comparison of time taken to dry maize in STD and OSD

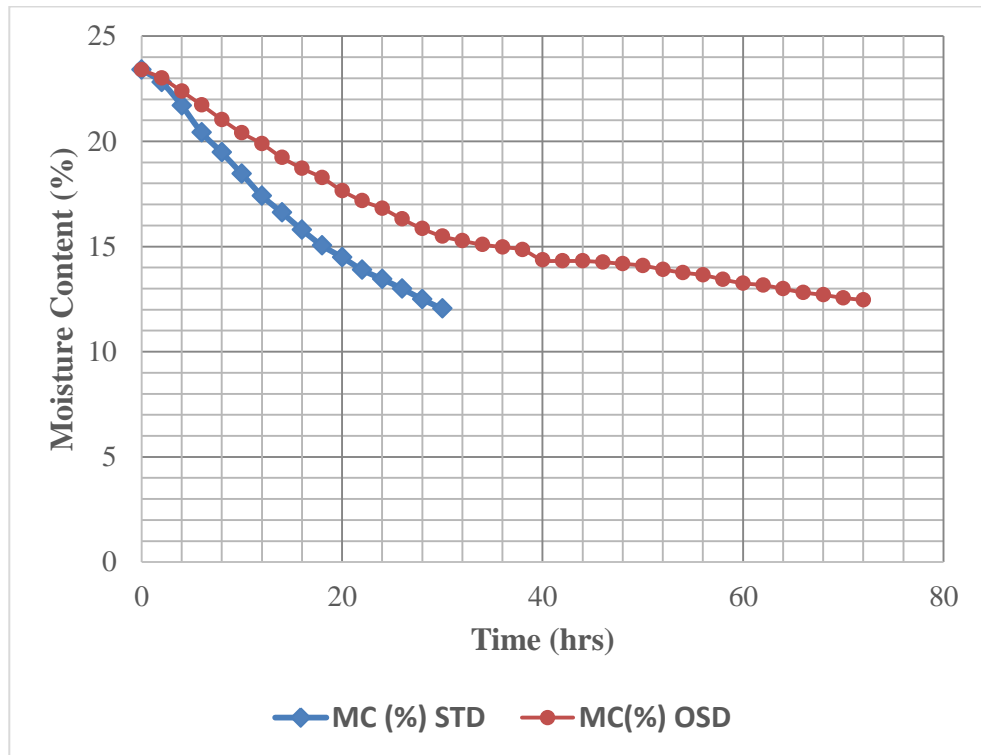
Figures 5.1, 5.2 and 5.3 show the reduction of moisture content over the drying period for the 3 experiments that were carried out. Experiment 1 was conducted between 16 and 23 May 2017. Experiment 2 was performed between 24 and 28 May 2017 while Experiment 3 was carried out between 29 May 2017 and 02 June 2017.



**Key:** MC (%) STD and MC (%) OSD is moisture content of maize dried in a Solar Tunnel Dryer and that dried in the open.

*Figure 5.1: Reduction of moisture content in OSD and STD (Experiment 1).*

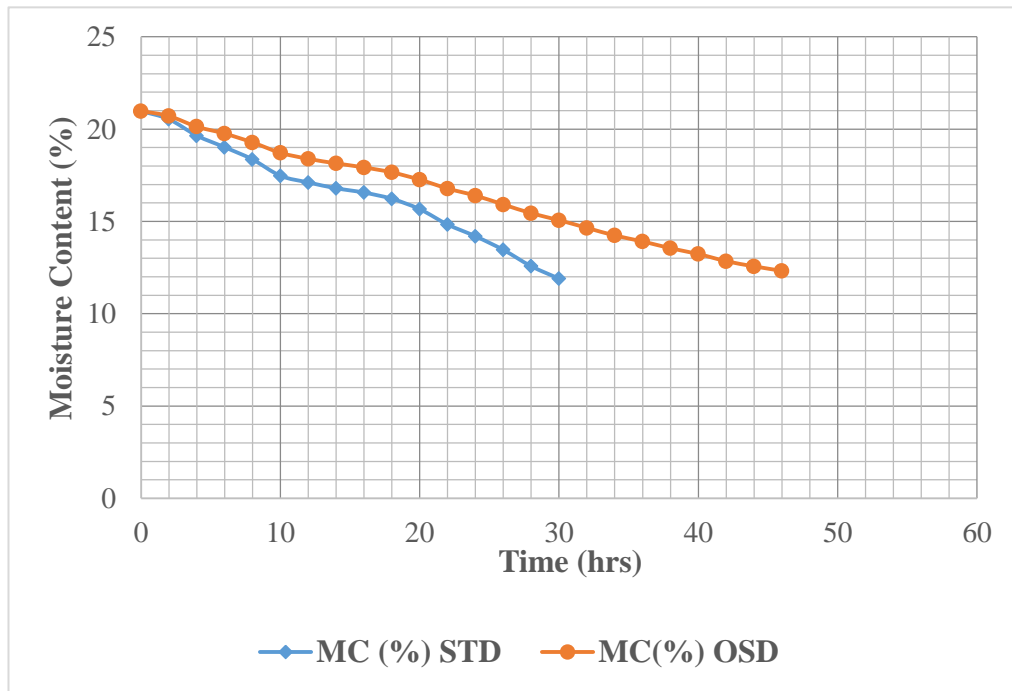
Figure 5.1 shows that the moisture content of the maize reduced from an initial figure of 27.68 % to 12.56 % in a period of 48 hours for the Solar Tunnel Dryer whereas it took 77.2 hours to attain a moisture content of 12.5 % for Open-Sun dried maize.



**Figure 5.2: Reduction of moisture content in OSD and STD (Experiment 2).**

In Figure 5.2, the initial moisture content at the start of the experiment was 23.4 %. For the maize dried in the Solar Tunnel Dryer, it took 28 hours to achieve the desired moisture content of 12.5 % and 72 hours for maize dried in the Open Sun.

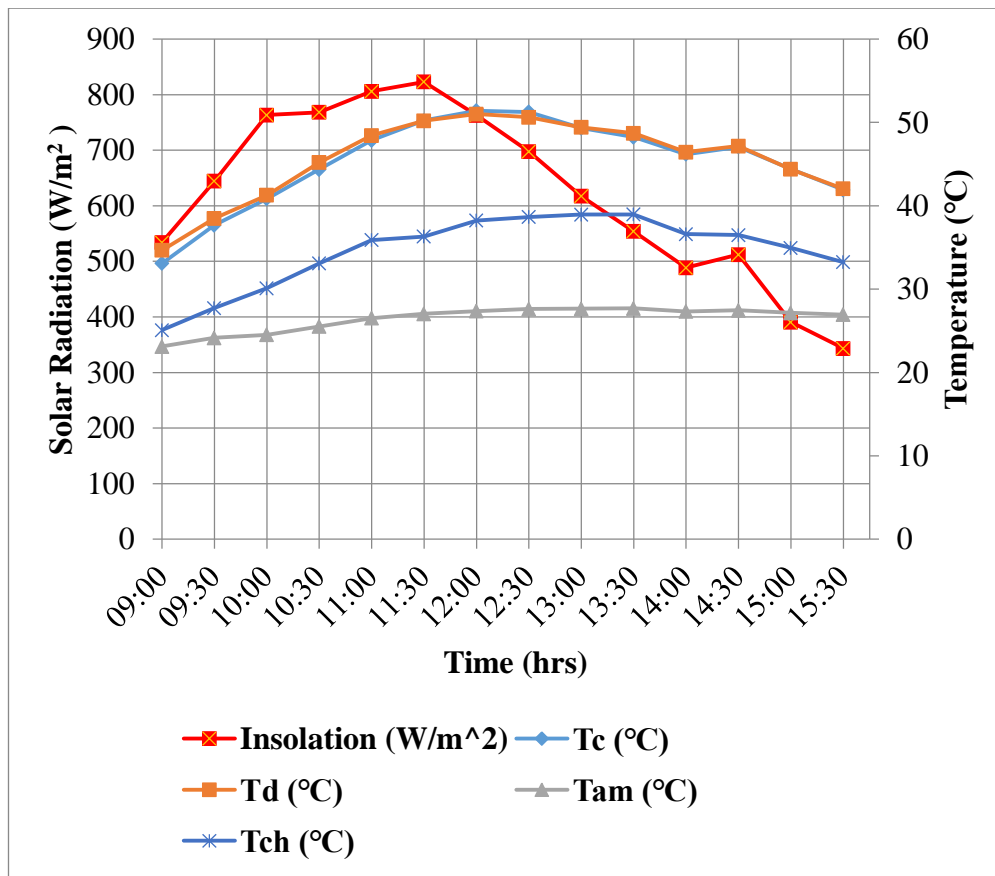
Experiment 3 which is depicted by Figure 5.3 shows that the initial moisture content of the maize at the start of the experiment was 20.98 % and this was reduced to 12.5 % in 28.5 hours for the maize dried in the Solar Tunnel Dryer while it took 44.6 hours to attain 12.5 % in Open Sun Drying.



**Figure 5.3:** Reduction of moisture content in OSD and STD (Experiment 3).

**5.2 Variation of temperature versus solar radiation during drying in all the experiments**

Figures 5.4, 5.5 and 5.6 show the variation of temperature and solar radiation with time over the drying period for all the 3 experiments carried out.

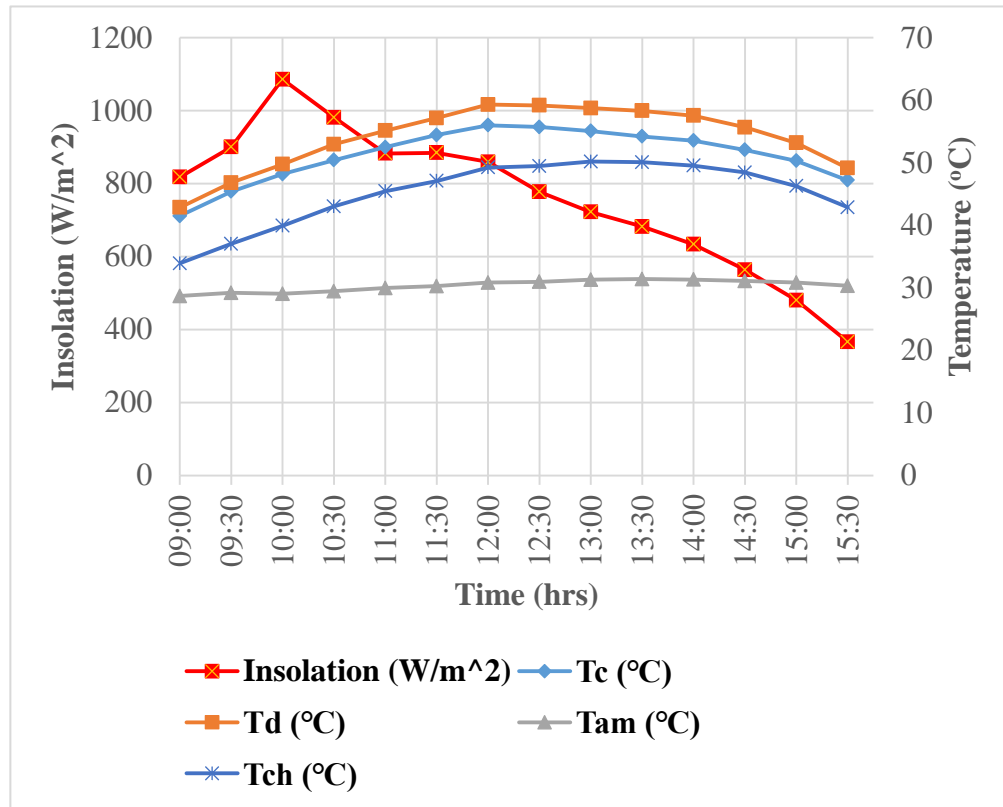


**Key:** Tam, Tc, Td and Tch represent ambient temperature and temperatures in the collector, drying and chimney sections respectively.

**Figure 5.4: Variation of temperature and solar radiation with time of the day (Experiment 1).**

Figure 5.4 shows the variation of temperature and solar radiation with time over the drying period for Experiment 1. The ambient mean temperature at the start of the drying day was lowest at a value of 23.1 °C and attained a maximum value of 27.7 °C at 13:30 hours. At 15:30 hours the temperature had reduced to 26.9 °C. An average mean temperature of 26.4 °C was registered for ambient temperature. The temperatures registered in the chimney ranged from 25.1 °C at 09:00 hours to 39.0 °C at 13:30 hours and decreasing to 33.2 °C by 15:30 hours; an average of 34.6 °C was recorded. As for the dryer and collector exits, temperatures recorded were not that different as shown by the values recorded at 09:00 hours; 34.7 °C and 33.1 °C. At 12:00 hours the temperatures were the same at 51 °C and reduced at the same rate to a value 42.0 °C at 15:30 hours. Average temperatures recorded were 45.6 °C and 45.3 °C, respectively. Solar radiation varied from 533.98 W/m<sup>2</sup> at 09:00 hours and

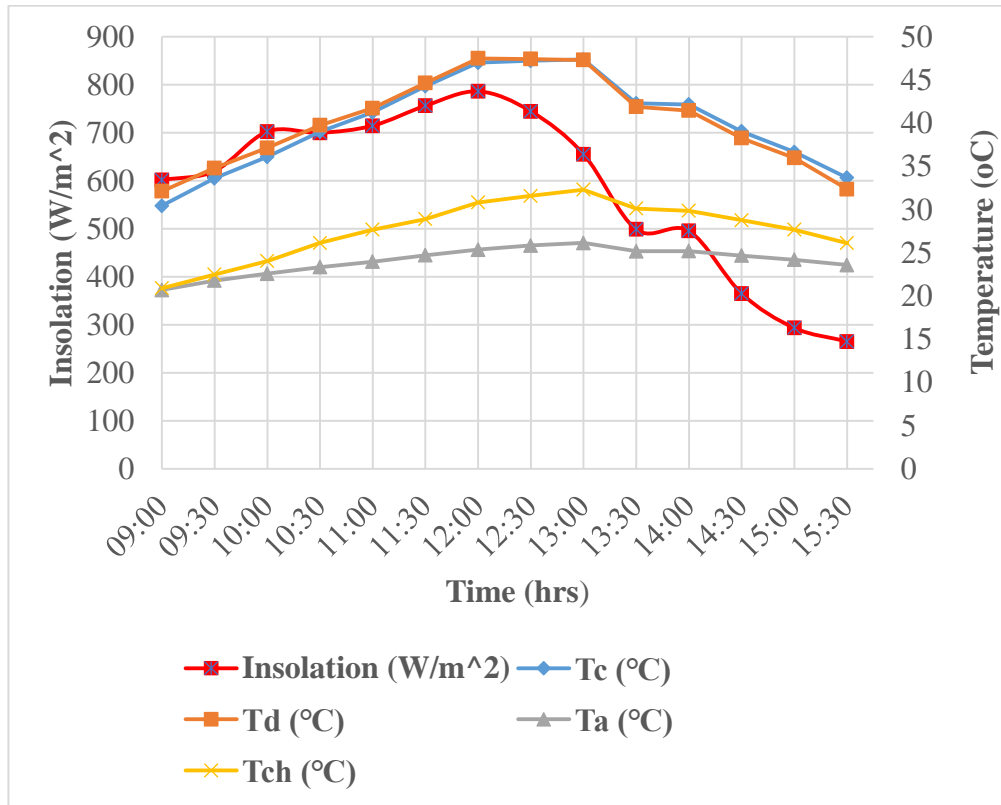
reached a peak of  $822.9 \text{ W/m}^2$  at 11:30 hours. The intensity of insolation reduced to  $343.4 \text{ W/m}^2$  at 15:30 hours. The average intensity registered was  $621.8 \text{ W/m}^2$ .



**Figure 5.5:** Variation of temperature and solar radiation with time of the day (Experiment 2).

Figure 5.5 depicts the variation of temperature and solar radiation with time of the day during Experiment 2. At 09:00 hours the ambient average temperature was  $28.7^{\circ}\text{C}$  and a maximum value was attained at 13:30 hours when the temperature was  $31.4^{\circ}\text{C}$ . By 15:30 hours the temperature reached  $30.3^{\circ}\text{C}$ . An average ambient temperature of  $30.3^{\circ}\text{C}$  was attained. The chimney temperature at 09:00 hours was  $33.9^{\circ}\text{C}$ , reaching a peak value of  $50.2^{\circ}\text{C}$  at 13:00 hours. At 15:30 hours, a temperature of  $42.9^{\circ}\text{C}$  was attained. The average chimney temperature was  $45.2^{\circ}\text{C}$ . The temperature of air exiting the collector unit was  $41.5^{\circ}\text{C}$  at 09:00 hours and rose to  $56.0^{\circ}\text{C}$  at 12:00 hours. By 15:30 hours the temperature reached  $47.2^{\circ}\text{C}$ . The average collector unit temperature was  $51.2^{\circ}\text{C}$ . As for the drying chamber, the temperature at 09:00 hours was  $42.9^{\circ}\text{C}$  and rose to  $59.3^{\circ}\text{C}$  at 12:00 hours. A decrease of temperature was recorded reaching  $49.1^{\circ}\text{C}$  at 15:30 hours. The mean

dryer temperature was 54.0 °C. Solar radiation varied from 817.7 W/m<sup>2</sup> at 09:00 hours and reached a peak of 1085.7 W/m<sup>2</sup> at 10:00 hours. The intensity of insolation reduced to 366.4 W/m<sup>2</sup> at 15:30 hours. The average intensity registered was 759.8 W/m<sup>2</sup>.



**Figure 5.6:** Variation of temperature and solar radiation with time of the day (Experiment 3).

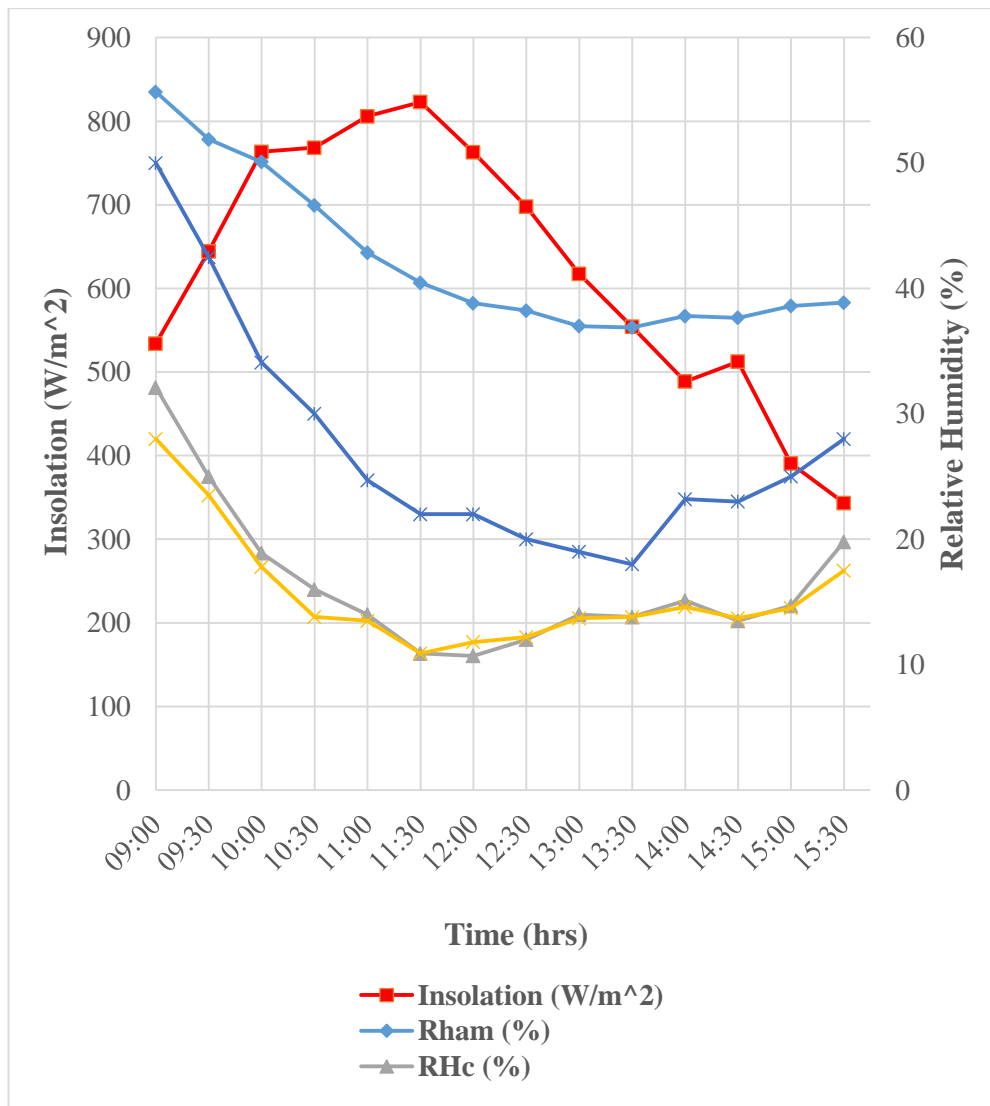
Figure 5.6 is showing the variation of temperature and solar radiation with time of the day. It can be seen that the mean ambient temperature was 20.9 °C at 09:00 hours and increased to 26.1 °C at 13:00 hours. There after the temperature started reducing until it reached 23.6 °C at 15:30 hours. The mean ambient temperature was 24.1 °C. As for the chimney, the temperature at 09:00 hours was also 20.9 °C but steadily increased until it peaked at 13:00 hours attaining a value of 32.3 °C. The reading at 15:30 hours was 26.1 °C. The average temperature for the chimney was 27.7 °C. Temperatures in the collector were 30.4 °C at 09:00 hours, 47.4 °C at 13:00 hours and 33.7 °C at 15:30 hours. On average the temperature in the collector was 40.0 °C. In the dryer, the temperature at 09:00 hours was 32.1 °C and increased to 47.5 °C at 12:00 hours. At 15:00 hours the temperature was 32.4 °C. The average drying chamber temperature was 40.2 °C. In this experiment, the solar radiation ranged from

601.62 W/m<sup>2</sup> at 09:00 hours and peaked at 12:00 hours when the recorded intensity was 786.16 W/m<sup>2</sup>. At 15:30 hours the value registered was 265.27 W/m<sup>2</sup>. The average intensity achieved was 585.62 W/m<sup>2</sup>.

### **5.3 Variation of relative humidity versus solar radiation during the drying period for all the experiments**

Figures 5.7, 5.8 and 5.9 depict the fluctuations of relative humidity versus solar radiation with time during the period of drying in the Solar Tunnel Dryer.

Figure 5.7 shows that the ambient relative humidity was at the highest at the start of the drying with a mean value of 55.7 % being recorded. The value reduced to 36.9 % by 13:30 hours and started increasing as the day went on, reaching a value of 38.9 % at the end of the day. The average ambient relative humidity was 42.2 %. In the chimney, the relative humidity ranged from 50 % at 09:00 hours to 18 % at 13:30 hours and increasing to 28 % by the end of the day. An average value of 27.3 % was attained. The values recorded for the dryer ranged from 28 % at 09:00 hours to 11.8 % at 12:00 hours with the value increasing to 17.5 % by the end of the day. The values registered in the collector unit ranged from 32.1 % at 09:00 hours to 10.7 % at 12:00 hours and the relative humidity increased to 19.8 % at the end of the day. Average values for the dryer and collector were 15.7 % and 16.5 % respectively.

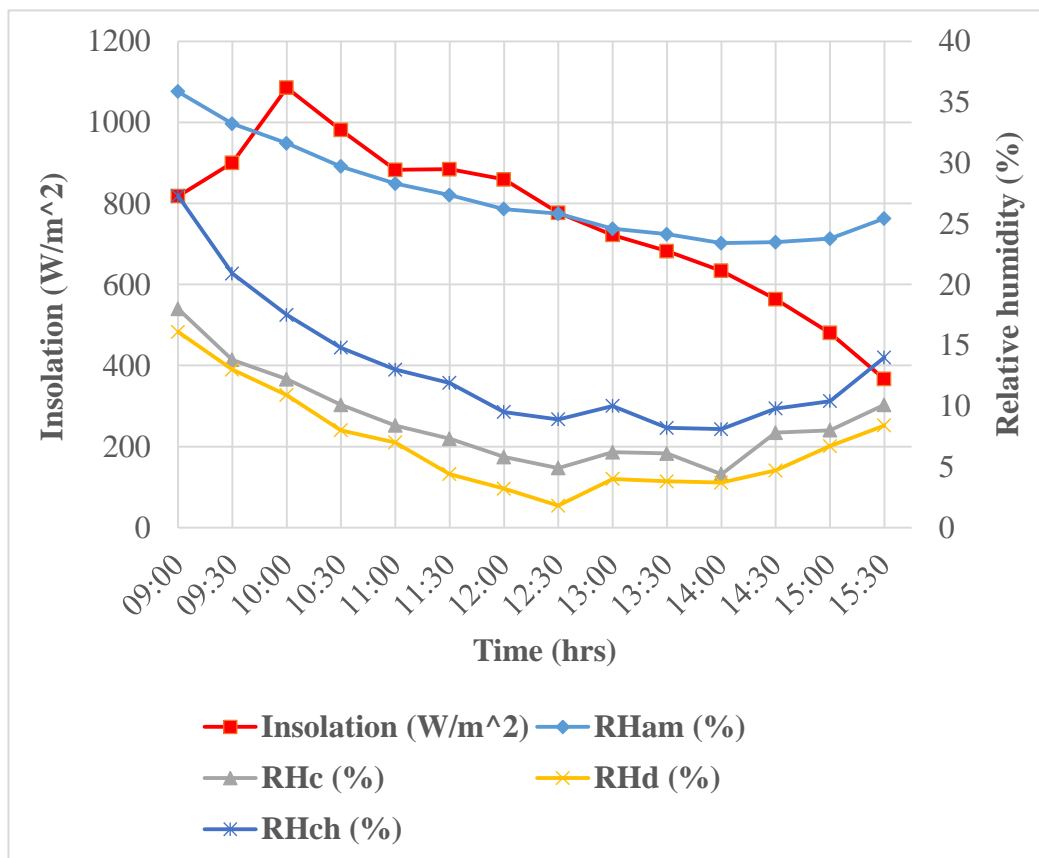


**Key:** RHam is ambient relative humidity, RHc, RHd and RHch is the relative humidity in the collector, drying and chimney sections respectively.

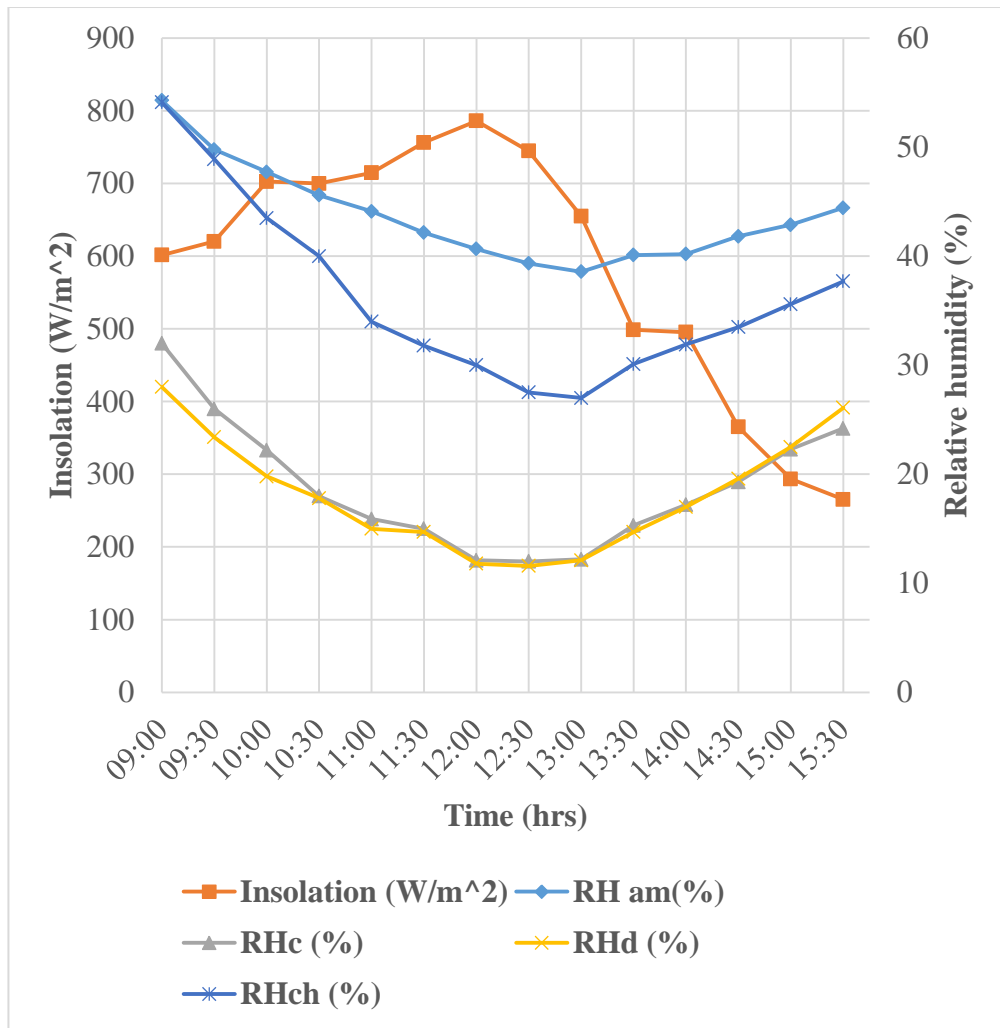
**Figure 5.7: Relationship of relative humidity against solar radiation over the drying period (Experiment 1).**

Figure 5.8 shows the relationship of relative humidity against solar radiation over the drying period. At 09:00 hours, the ambient relative humidity was 35.9 %. This value reached a minimum of 23.4 % at 14:00 hours. The relative humidity then started increasing steadily until it reached 25.4 % at 15:30 hours. The average relative humidity was 27.3 %. In the chimney, the relative humidity at 09:00 hours was 20.9 % and a minimum value of 8.1 % was attained at 14:00 hours. This value started increasing as the day progressed reaching a value of 14 % at 15:30 hours. The mean

relative humidity in the chimney was 13.2 %. The relative humidity observed in the collector at 09:00 hours was 18 %. At 14:00 hours, the relative humidity was 4.4 % and this value started increasing reaching a value of 10.1 % at 15:30 hours. A mean relative humidity value in the collector unit was 8.8 %. The drying chamber relative humidity at 09:00 hours was 16.1 %. A minimum value of 1.8 % was attained at 12:30 hours. The relative humidity started increasing until it reached a value of 8.4 % at 15:30 hours. The average relative humidity in the drying chamber was 6.8 %.



**Figure 5.8:** Relationship of relative humidity against solar radiation over the drying period (Experiment 2).



**Figure 5.9: Relationship of relative humidity against solar radiation over the drying period (Experiment 3).**

Figure 5.9 depicts the relationship of relative humidity against solar radiation over the drying period. At 09:00 hours the average ambient relative humidity was 54.1 % and the minimum was attained at 13:00 hours at a value of 38.6 %. As the day progressed, the relative humidity started increasing reaching a value of 44.4 % at 15:30 hours. The average ambient relative humidity was 43.7 %. As for the chimney, the relative humidity reading at 09:00 hours was 54.1 % and reduced to 27 % at 13:00 hours. The value increased to 37.7 % by 15:30 hours. The average chimney relative humidity was 36.1 %. The relative humidity of the air exiting the solar collector was 32 % at 09:00 hours and reduced to 12 % at 12:30 hours. The value increased to 24.2 % by 15:30 hours. The overall mean relative humidity of air exiting the collector unit was 18.8 %. In the drying chamber, the relative humidity at 09:00

hours was 28 %. This value reduced to 11.6 % at 12:30 hours. As the day progressed, the relative humidity increased to 26.1 % at 15:30 hours. The mean dryer relative humidity was 18.2 %

The solar radiation observed was 601.6 W/m<sup>2</sup> at 09:00 hours and peaked at 12:00 hours registering a value of 786.2 W/m<sup>2</sup>. As the day progressed into late afternoon, the solar radiation reached a value of 265.3 W/m<sup>2</sup> at 15:30 hours. The average solar radiation observed during the experiment was 585.6 W/m<sup>2</sup>.

#### 5.4 Thin layer modeling

The statistical parameters obtained to authenticate the fit of each model to the observed data during the maize drying experiments are presented in the Tables 3, 4 and 5 respectively.

**Table 3 Regression analysis for Experiment 1**

<b>Model No (Refer to Table 1)</b>	<b>Order of best fit</b>	<b>Constants</b>	<b><math>\chi^2</math></b>	<b>RMSE</b>	<b>R<sup>2</sup></b>	
			<b>*10<sup>-05</sup></b>	<b>*10<sup>-03</sup></b>		
<b>13</b>	<b>1</b>	<b>a</b>	<b>1.00194</b>	<b>2.8223</b>	<b>4.869</b>	<b>0.9991</b>
		<b>k</b>	<b>0.01365</b>			
		<b>n</b>	<b>1.04651</b>			
		<b>b</b>	<b>4.824E-05</b>			
11	2	k	0.02159	2.7193	4.892	0.9991
		I	1.25992			
		n	1.05223			
2	3	k	0.01328	2.601	4.892	0.9991
		n	1.05219			
4	4	a	1.14415	2.732	4.903	0.9991
		k	0.01359			
14	5	a	0.23739	3.279	4.992	0.9991
		k	0.02309			

		b	-0.02295			
		g	0.25445			
		c	0.78492			
		h	0.01497			
9	6	a	1.01497	2.867	5.023	0.9991
		k	0.01642			
		g	0.55059			
5	7	a	-0.01398	3.092	5.097	0.999
		k <sub>1</sub>	0.90654			
		b	1.01387			
		k <sub>2</sub>	0.01639			
12	8	a	-0.01483	3.027	5.162	0.999
		b	7.702E-05			
		c	-7.597E-08			
6	9	a	-0.01476	2.901	5.166	0.999
		b	7.212E-05			
3	10	a	1.01046	3.451	5.635	0.9988
		k	0.01627			
1	11	k	0.01589	5.494	7.262	0.998
7	12	a	1	5.733	7.262	0.998
		k	0.01589			
10	13	a	0.00457	6.661	7.656	0.9978
		k	0.08036			
		b	0.19629			
8	14	k	0.0175	73.853	26.066	0.9749
		n	1			

**Key:** 1 Highest  $R^2$  and lowest  $X^2$  and RMSE – Most accurate model

14 Lowest  $R^2$  and highest  $X^2$  and RMSE – Least accurate model

**Table 4 Regression analysis for Experiment 2**

<b>Model No (Refer to Table 1)</b>	<b>Order of best fit</b>	<b>Constants</b>	<b><math>\chi^2</math></b> <b>*10<sup>-05</sup></b>	<b>RMSE</b> <b>*10<sup>-03</sup></b>	<b>R<sup>2</sup></b>	
<b>13</b>	<b>1</b>	<b>a</b> <b>k</b> <b>n</b> <b>b</b>	<b>1.00466</b> <b>0.02354</b> <b>1.1652</b> <b>0.00765</b>	<b>1.7104</b>	<b>8.954</b>	<b>0.9995</b>
14	2	a k b g c h	-0.06981 0.86366 0.87073 0.01801 0.1984 0.12827	2.3843	9.651	0.9994
12	3	a b c	-0.02131 -3.334E-05 7.0991E-06	5.8599	1.725	0.998
4	4	a k c	0.76005 0.03673 0.25873	6.7192	1.847	0.9977
6	5	a b	-0.02402 2.60E-04	8.5141	2.159	0.9969
5	6	a k <sub>1</sub> b k <sub>2</sub>	0.15521 0.88933 0.99203 0.02299	12.6204	2.432	0.9961
2	7	k n	0.02496 0.97693	14.0982	2.777	0.9949
11	8	k I n	0.01682 0.8169 0.97689	15.1827	2.777	0.9949
9	9	a k g	1.00563 0.02361 3.31389	15.3321	2.79	0.9948
7	10	a k	1.003846 0.011733	14.3876	2.805	0.9948
3	11	a k	1.00385 0.02351	14.3876	2.805	0.9948
1	12	k	0.023298	13.7518	2.839	0.9947

10	13	a	1	15.8675	2.839	0.9947
		k	0.023298			
		b	1			
8	14	k	0.01986	173.8186	9.749	0.937
		n	1			

**Key:** 1 Highest  $R^2$  and lowest  $\chi^2$  and RMSE – Most accurate model

14 Lowest  $R^2$  and highest  $\chi^2$  and RMSE – Least accurate model

**Table 5 Regression analysis for Experiment 3**

Model No (Refer to Table 1)	Order of best fit	Constants	$\chi^2$	RMSE	$R^2$	
				* $10^{-05}$	* $10^{-03}$	
13	1	a	<b>0.99569</b>	<b>27.8466</b>	<b>3.613</b>	<b>0.9869</b>
		k	<b>-0.012477</b>			
		n	<b>0.00239</b>			
		b	<b>0.78152</b>			
6	2	a	-0.01386	24.7921	3.682	0.9864
		b	-3.727E-07			
5	3	a	0.50425	29.6283	3.727	0.986
		k <sub>1</sub>	0.01648			
		b	0.49985			
		k <sub>2</sub>	0.01647			
4	4	a	2.70509	28.5084	3.805	0.9854
		k	0.00542			
		c	-1.70614			
12	5	a	-0.02008	9.3424	2.178	0.9852
		b	0.00067			
		c	-1.631E-05			
10	6	a	-8.17973	31.4763	3.998	0.9839
		k	0.03331			
		b	0.93576			
2	7	k	0.01189	32.202	4.196	0.9823
		n	1.10974			

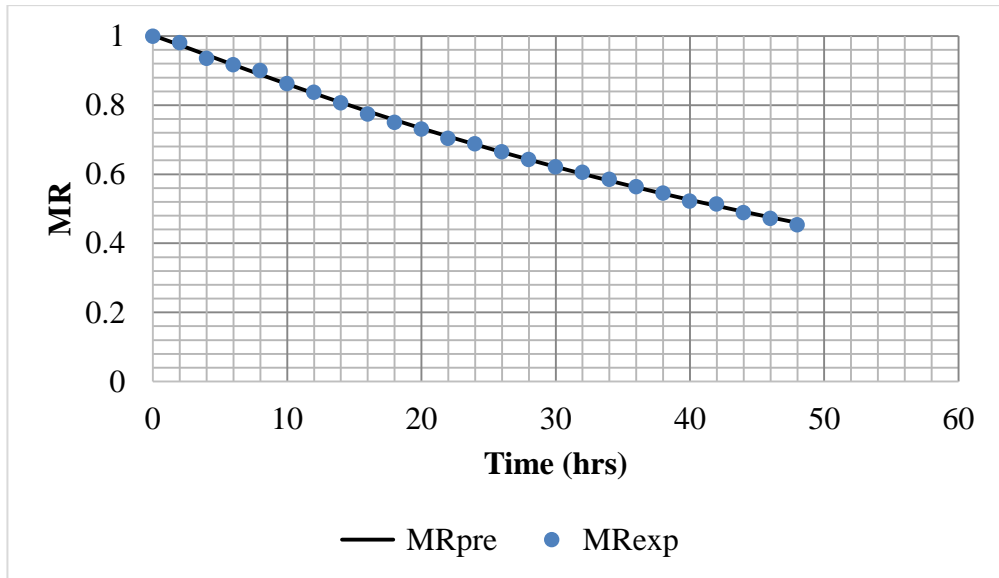
11	8	k	0.01726	34.6791	4.196	0.9823
		l	1.18255			
		n	1.10974			
14	9	a	0.71638	51.3246	4.478	0.9798
		k	0.01721			
		b	0.29635			
		g	0.01743			
		c	-0.01269			
		h	0.85609			
3	10	a	1.00864	37.4002	4.523	0.9794
		k	0.017063			
9	11	a	0.58422	42.3313	4.636	0.9784
		k	0.01661			
		g	0.01661			
1	12	k	0.01661	36.6871	4.6364	0.9784
7	13	a	0.00493	41.9382	4.789	0.9769
		k	3.3174			
8	14	k	0.01425	137.9136	8.685	0.9241
		n	1			

**Key:** 1 Highest  $R^2$  and lowest  $X^2$  and RMSE – Most accurate model

14 Lowest  $R^2$  and highest  $X^2$  and RMSE – Least accurate model

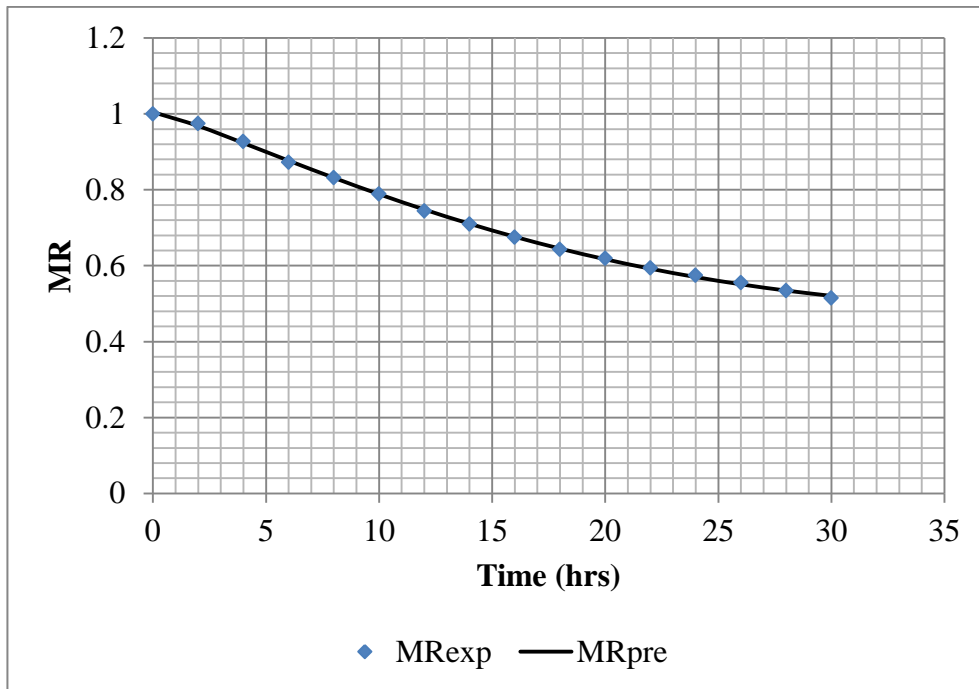
### 5.5 Comparison of predicted and experimental moisture ratio during the drying period

Figures 5.10, 5.11 and 5.12 show the closeness of fit of the experimental moisture ratio to the predicted moisture ratio using the excel solver add- in application.

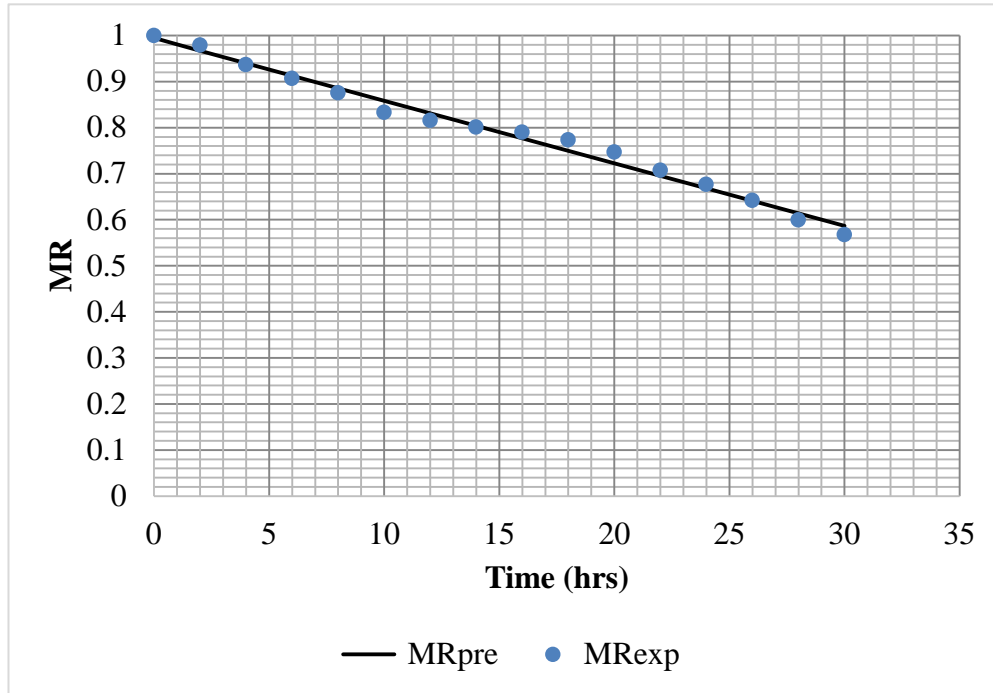


Key: MRpre is predicted moisture ratio and MRexp is experimental moisture ratio

**Figure 5.10: Regression analysis for Midilli mathematical model (Experiment 1).**



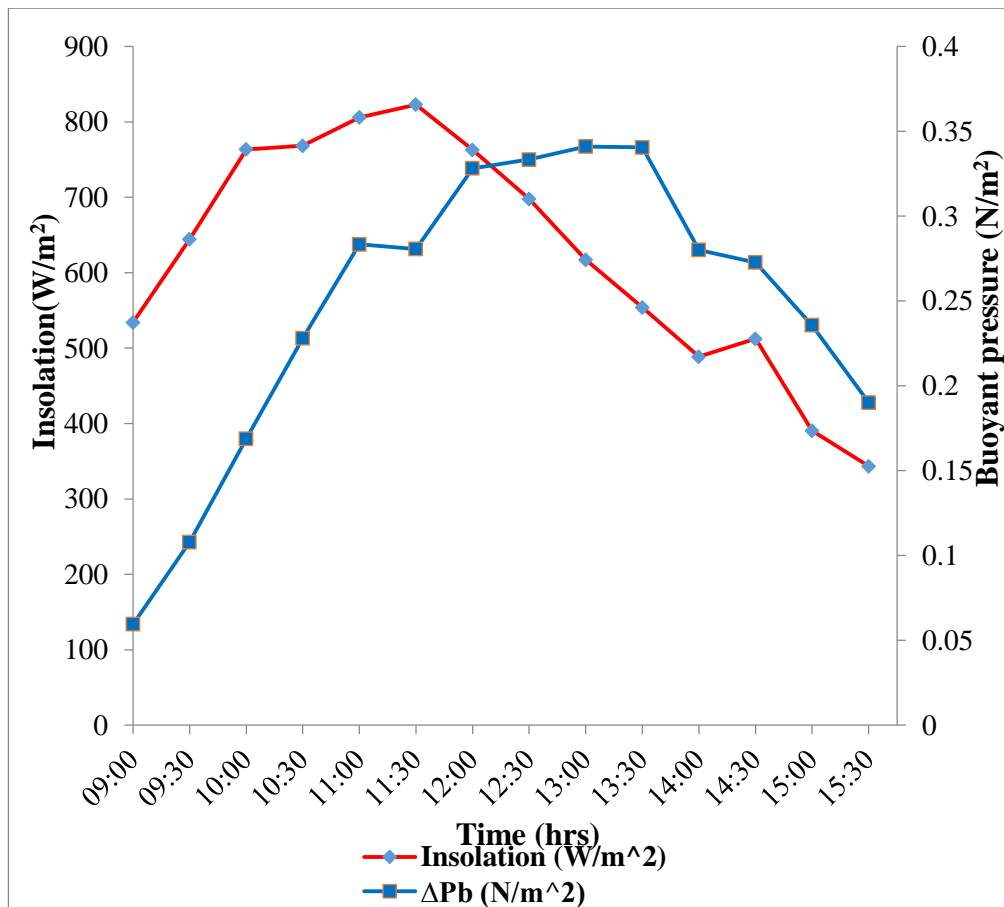
**Figure 5.11: Regression analysis for Midilli mathematical model (Experiment 2).**



*Figure 5.12: Regression analysis for Midilli mathematical model (Experiment 3).*

### 5.6 Performance of solar chimney

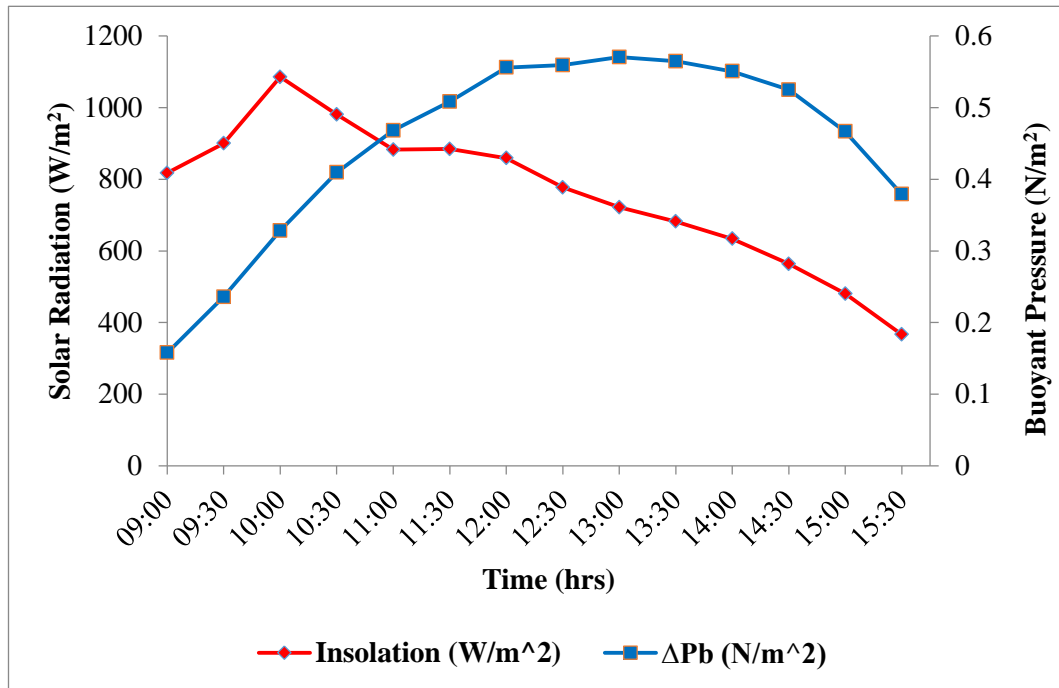
Using equation (4.5), the buoyancy pressure head was calculated for all the 3 experiments. Graphs showing variation of buoyant pressure and solar insolation against time are shown in Figures 5.13, 5.14 and 5.15 respectively.



**Key:** ΔPb is the buoyant pressure

**Figure 5.13:** Variation of buoyant pressure and insolation with drying time (Experiment 1).

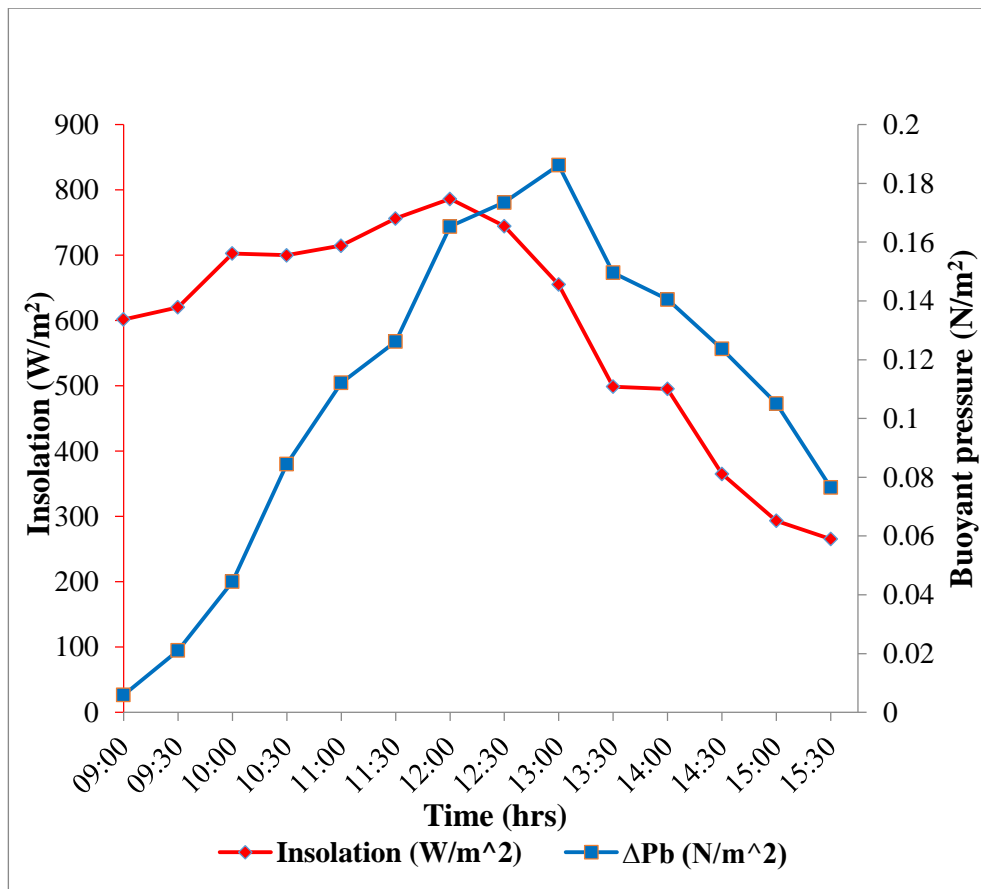
Figure 5.13 shows that at 09:00 hours the intensity of solar radiation was 534 W/m<sup>2</sup> whereas the buoyant pressure was 0.059 N/m<sup>2</sup>. The solar radiation reached a peak at 12:00 hours recording a value of 762.8 W/m<sup>2</sup>. The intensity started reducing until it reached a value 343.4 W/m<sup>2</sup> at 15:30 hours. The buoyant pressure increased until it attained a maximum value of 0.341 N/m<sup>2</sup> at 13:00 hours. It then reduced to 0.190 N/m<sup>2</sup> at 15:30 hours.



**Figure 5.14:** Variation of buoyant pressure and insolation with drying time (Experiment 2).

Figure 5.14 depicts the variation of the buoyant pressure which ranged from 0.158 N/m<sup>2</sup> at 09:00 hours to 0.379 N/m<sup>2</sup> at 15:30 hours. A peak of 0.57 N/m<sup>2</sup> was attained at 13:00 hours. The solar radiation varied from 817.7 W/m<sup>2</sup> at 09:00 hours to 366.4 W/m<sup>2</sup> at 15:30 hours. The intensity reached a maximum at 10:00 hours attaining a value of 1085.7 W/m<sup>2</sup>.

In Figure 5.15 for Experiment 3, it shows how the buoyant pressure varied over the drying time. At 09:00 hours the pressure was 0.059 N/m<sup>2</sup> and rose to a value of 0.186 N/m<sup>2</sup> at 13:00 hours. This reduced to 0.077 N/m<sup>2</sup> at 15:30 hours. The intensity of solar radiation ranged from 601.6 N/m<sup>2</sup> at 09:00 hours attaining a maximum value of 786.2 W/m<sup>2</sup> at 12:00 hours. As the day progressed, the intensity reduced to 265.3 W/m<sup>2</sup> at 15:30 hours. In the work undertaken by Cherotich (2016) the buoyant pressure ranged between 0.3016 and 0.1530 N m<sup>2</sup>.

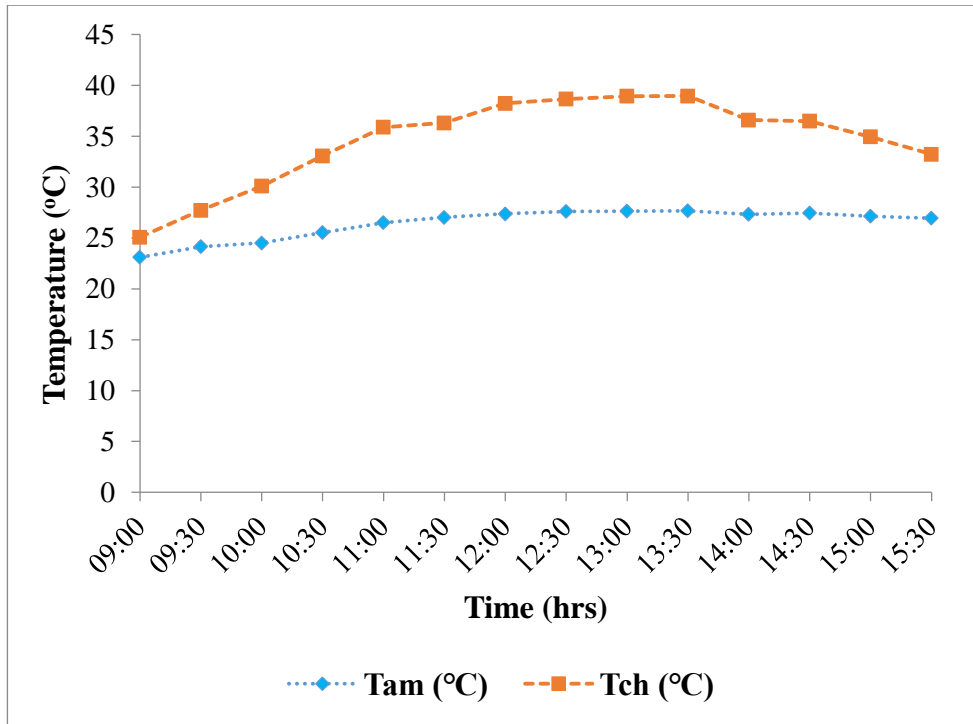


*Figure 5.15: Variation of buoyant pressure and insolation with drying time (Experiment 3).*

### 5.6.1 Comparison of ambient and chimney temperature during the drying period

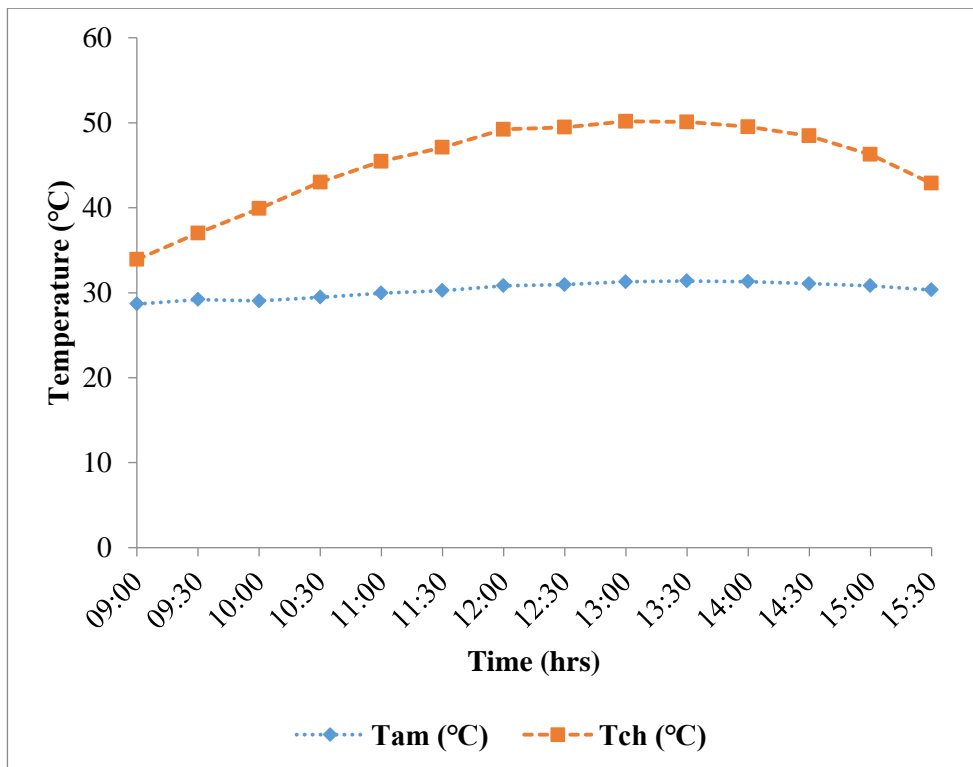
Figures 5.16, 5.17 and 5.18 shows the air temperatures attained during the course of the drying experiments for the ambient and chimney section.

Figure 5.16 is displaying that the chimney temperature ranged from 25.1°C at 09:00 hours to 39 °C at 13:30 hours. This value reduced to 33.2 °C by the end of the drying session. On the other hand the ambient temperature ranged between 23.1 to 27.7 °C at 09:00 and 13:30 hours, respectively. At 15:30 hours the temperature had reduced to 26.9 °C. The mean temperature difference was 8.2 °C.



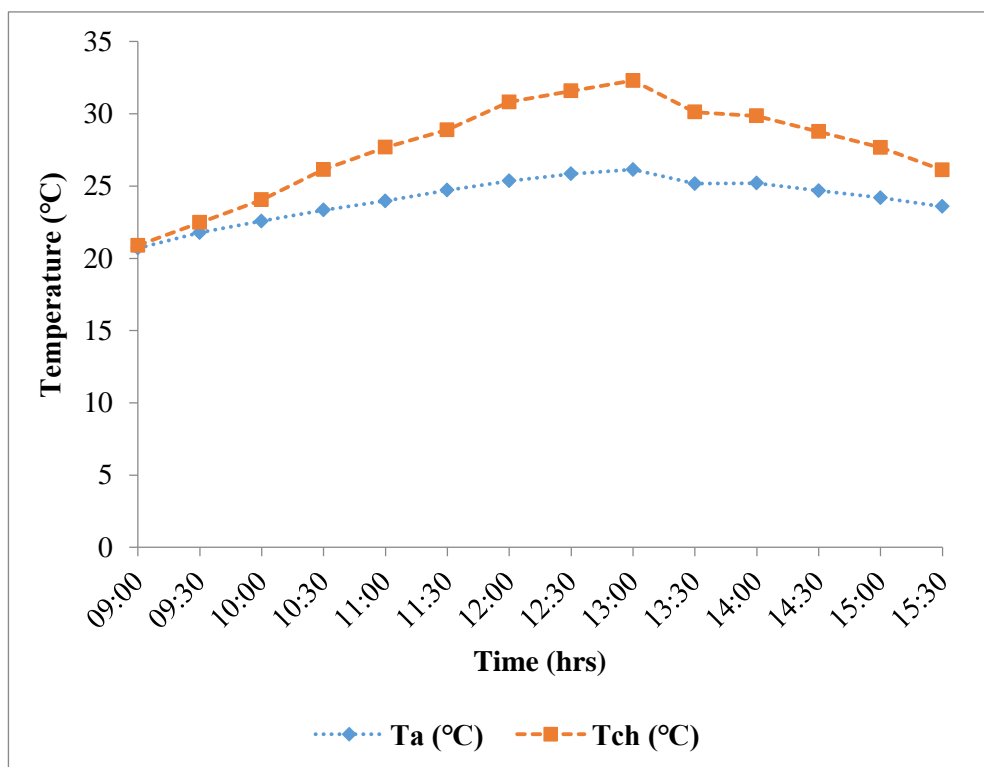
**Key:** Tam and Tch is ambient and chimney air temperature respectively

*Figure 5.16: Variation of ambient and chimney temperature with drying time (Experiment 1).*



**Figure 5.17: Variation of ambient and chimney temperature with drying time (Experiment 2).**

The results shown in Figure 5.17 show that the chimney temperature ranged from 33.9 °C to 50.2 °C between 09:00 and 13:00 hours. This value decreased to 42.9 °C at 15:30 hours. The values of ambient temperature ranged from 28.7 °C to 31.4 °C at 09:00 and 13:00 hours. The temperature at 15:30 hours was 30.3 °C. A higher temperature difference was attained in this experiment with a value of 14.9 °C being registered.



**Figure 5. 18: Variation of ambient and chimney temperature with drying time (Experiment 3).**

As shown in Figure 5.18, the chimney temperature varied from 20.9 to 32.3 °C between 09:00 hours and 13:00 hours. By 15:30 hours the temperature had reached 26.1 °C. On the other hand, the ambient temperature was between 20.9 and 26.1 °C at 09:00 13:00 hours, respectively. The attained value at 15:30 hours was 23.6 °C. The difference between the ambient and chimney temperature was only 3.6 °C in this experiment.

## **5.7 Aflatoxins levels in maize**

The results are:

Solar tunnel dryer (STD)	–	8.37 ppb
Open-sun drying (OSD)	–	11.57 ppb
Straight from the field (SFF)	–	8.63 ppb

## **5.8 Closing remarks**

In this Chapter, the results of all the investigations carried out have been presented. The next Chapter presents the discussion.

## CHAPTER VI

### 6.0 DISCUSSION

In this Chapter, the results obtained in the previous Chapter are discussed. The discussion will follow the way the results have been presented.

#### 6.1 Comparison of time taken to dry maize in STD and OSD

During Experiment 1, the STD maize took 48 hours to reach a moisture content of 12.56 % from initial moisture content of 27.7 % wet basis as compared to 78 hours for OSD to reach 12.42 %. This resulted in net saving of 38.5 % in drying time when compared to OSD. It should be noted that these hours are cumulative. Each drying day was 7 hours. In the work by Iqbal and Ahmad (2014), maize cobs with an initial moisture content of 26.1 % were reduced to a moisture content of 18.9 % in four days using a solar passive dryer. This showed a reduction of moisture by 7.2 % in 32 hours of drying. This is almost comparable to the 10.9 % reduction in moisture content after drying for 32 hours, in this research. Irtwange and Adebayo (2009), in their work found similar results when maize with a moisture content of 32.8 % was reduced to a moisture content of 13 % in four days (32 hours). On the other hand, it took eight days to attain 13 % moisture content in sun dried maize. Mumba (1995), designed and developed a solar dryer dependent on forced convection as mode of air movement. This dryer was powered by a photovoltaic system as it is adaptable in areas without grid electricity. Maize with a moisture content of 33.3 % was reduced to 20 % in one day. In the work by Eke and Arinze (2011), maize at initial moisture content of 30 % was dried to 12 %.

Experiment 2 shows that the moisture content was reduced from 23.4 % wet basis to 12.5 % in 28 hours using a STD were as it took 72 hours for OSD to attain a safe storage moisture content of 12.5 %. This resulted in a net saving of 60 % in drying time when compared to OSD.

As for Experiment 3, it took 28 hours for maize dried in the STD to reach a safe storage moisture content of 12.6 % from an initial moisture content of 21 % as opposed to 44 hours for OSD. This is comparable to the results found by Folaranmi (2008). Maize at a moisture content of 20 % wet basis was reduced to a moisture content of 12.5 % in three days. Each day of drying had nine hours. In his work the

average dryer temperature was 45 °C. In this experiment the average dryer temperature was 40.2 °C. In the work by Agbossou et al. (2016) maize cobs were dried from a moisture content of 37 % to 13 % in 20 hours. It took an average of 72 hours for OSD maize to reach the safe storage moisture of 13 %. A net saving of 36.4 % in drying hours was attained.

In all the 3 experiments, all drying takes place within the falling rate regime (Ekechukwu, 1999). This is because the maize was partially dried in the field before harvesting, implying that the free moisture had evaporated.

It is also worth mentioning that at the end of each experimental day, the maize samples that were being dried in the dryer would be sealed in an airtight bag to avoid moisture ingress and egress during the night thus distorting the last measured weight at the beginning of drying on the next day.

## **6.2 Variation of temperature versus solar radiation during drying in all the experiments**

Figures 5.4, 5.5 and 5.6 for Experiments 1, 2 and 3 respectively all show that the ambient temperature was the least in all experiments followed by the temperature in the chimney. Temperatures in the collector and dryer units were not that different though there was a pattern of dryer chamber temperatures being slightly above that of the collector. Depending on the time of the experiment, the intensity of solar radiation was different with maximum intensities being recorded as follows: Experiment 1- 822.88 W/m<sup>2</sup> recorded at 11:30 hours, Experiment 2- 1085.69 W/m<sup>2</sup> recorded at 10:00 hours and Experiment 3- 786.16 W/m<sup>2</sup> registered at 12:00 hours. The Figures 5.4, 5.5 and 5.6 also show that despite the solar intensity going down, the collector and dryer temperatures remained high until late in the day when they started decreasing.

The maximum temperatures recorded in the drying chamber for Experiments 1, 2 and 3 were 51.0 °C at 12:00 hours, 59.3 °C at 12:00 hours and 47.5 °C at 12:00 hours, respectively. The maximum temperatures do not necessarily coincide with the time of maximum insolation apart from Experiment 3 when maximum values of temperature and insolation were recorded at the same time. This can be explained by the slow build up of heat retained in the dryer.

Average temperature differences between the collector and ambient temperature for the 3 experiments were 18.84 °C, 20.84 °C and 15.92 °C, respectively. The mean daily ambient temperature ranged from 23.1 °C to 27.7 °C, 28.1 °C to 31.4 °C and 20.7 °C to 26.1 °C for Experiments 1, 2 and 3, respectively. As for the solar radiation, the values ranged from 343.4 W/m<sup>2</sup> to 822.9 W/m<sup>2</sup>, 366.4 W/m<sup>2</sup> to 1085.7 W/m<sup>2</sup> and 265.3 W/m<sup>2</sup> to 786.2 W/m<sup>2</sup> according to the order in which the experiments were done.

In the work by Agbossou et al. (2016), the mean daily temperatures recorded were 29.5 °C to 38.6 °C were as the solar radiation ranged from 289.9 W/m<sup>2</sup> to 774.8 W/m<sup>2</sup>. The high ambient temperature can be attributed to the fact that West Africa experiences summer during this time of the year and rainy season. The low intensity of solar radiation can be explained by intermittent rain clouds.

### **6.3 Variation of relative humidity versus solar radiation during the drying period for all the experiments**

The Figures 5.7, 5.8 and 5.9 show the variation of relative humidity against solar radiation in all the 3 experiments.

All the graphs show similar relationships were the ambient relative humidity is highest at the start of the experimentation at 09:00 hours and reduces as the day progresses. After midday the relative humidity starts rising up again until the end of the day.

The relative humidity in the chimney follows that of the ambient air. The collector and dryer sections recorded the lowest relative humidity values as the intensity of the sun increased. For all the three experiments, the ambient relative humidity was higher than that in the drying chamber by the following percentages: 62.8 %, 75.1 % and 58.4 % respectively. Average values of relative humidity in the drying air exiting the chimney are 27.3 %, 13.2 % and 36.1 % respectively. This shows that there is still a high drying potential in the drying air since ideally the drying air exiting the dryer should have a 100 % relative humidity (Mastekbayeva et al., 1998).

#### **6.4 Thin layer modeling**

According to the statistical analysis, experiments 1 to 3 all gave the Midilli mathematical model as the best fitting. Statistical parameters of reduced chi-square ( $\chi^2$ ), root mean square error (RMSE) and coefficient of determination ( $R^2$ ) were used to compare the goodness of fit. The constants and coefficients are shown in Tables 3-5 above. The models have been presented according to the best fit.

The average drying temperature in the drying chamber during the experiments was 46 °C, 54 °C and 40.2 °C, respectively. Corrêa et al. (2011), reported that the Logarithmic and Midilli were best fitting to the observed drying data. They however picked on the Logarithmic model since it did not have too many parameters. The drying temperature ranged from 45 °C to 65 °C in the drying oven. In the work by Agbossou et al. (2016), the drying temperature ranged from 40 °C to 60 °C. Air movement was by forced convection using a blower. The model that best fitted to the observed drying data was the Midilli. Ajala et al. (2012), found the Logarithmic model to be best fitting to the drying observed data. The drying was done in a temperature ranging from 60 °C to 70 °C using a convective hot air dryer. In the work of Hossain (2011) it was found that the best fitting model was the Page model. Experiments were done to determine optimum temperature and thin layer drying kinetics of quality seed maize using a hybrid solar dryer. It was found that the optimum temperature of drying seed maize was 42 °C.

#### **6.5 Comparison of predicted and experimental moisture ratio during the drying period**

Figures 5.10, 5.11 and 5.12 show the regression analysis using the excel solver add-in for the best fitting model. They compare the experimental and predicted moisture ratio at any particular time of the drying process for validation of the established model. These values lay around the straight line. The Midilli model provided a satisfactorily good conformity between the predicted and experimental moisture ratios. The predicted data generally banded around the straight line showing the suitability of this model in describing the solar drying behaviour of maize grains (Agbossou et al., 2016).

## **6.6 Performance of solar chimney**

In all the experiments, the average buoyant pressure head ranged from 0.246450703 N/m<sup>2</sup>, 0.44858892 N/m<sup>2</sup> to 0.108192724 N/m<sup>2</sup> which were all positive values. This was sufficient to achieve air movement by natural convection.

## **6.7 Aflatoxins levels in maize**

Allowable Aflatoxins concentration levels which can trigger action to be taken by health officials differ from country to country and regions. In Zambia, the acceptable concentration level is 10 ppb. This is according to the Zambia Bureau of Standards, ZS 186 of 2004. The USA allows 20 ppb whereas in the European Union, acceptable levels are between 4 ppb and 10 ppb depending on whether it is ready to eat corn or meant for further processing. The acceptable levels for straight feedstuffs like maize and its products, the European levels the B<sub>1</sub> Mycotoxin is 20 – 50 ppb whereas for complete feedstuffs for cattle and sheep except their young ones is 20 ppb. In the United States of America, the B<sub>1</sub> concentration acceptable for maize products for beef cattle, swine and poultry is between 100 – 300 ppb (Mazumder and Sasmal, 2001). According to the results obtained, maize that was dried in the open had higher Aflatoxins concentration levels according to Zambian standards. However, it is worth noting that the levels can be acceptable depending on the further treatment or use of the grain.

## **6.8 Closing remarks**

All results have been discussed in this Chapter. Conclusions and Recommendations are presented in the next Chapter.

## CHAPTER VII

### 7.0 CONCLUSIONS AND RECOMMENDATIONS

#### 7.1 Conclusions

In this Chapter, the conclusions and recommendations drawn from the study are presented. The attainment of each specific objective is specifically explained.

The following conclusions can be made:

##### 7.1.1 To design and fabricate the natural convection Solar Tunnel Dryer

(i) The dryer was successfully designed and fabricated. The designed natural convection Solar Tunnel Dryer successfully managed to reduce the moisture content of cob maize in less time compared to natural open sun drying.

(ii) Drying time reduced as follows in the 3 experiments: in Experiment 1, it took 48 hours in the STD as opposed to 76 hours in OSD to reduce the moisture content of the cob maize from 27.7 % to 12.5%. In Experiment 2, the moisture content was reduced from 23.4 % to 12.5 % in 28 hours using a STD against 72 hours in OSD. In the third and final experiment (Experiment 3), a total time of 28 hours was taken to reduce the moisture content from 21 % to 12.5 % as opposed to 44 hours in OSD.

(iii) The entire drying process of maize cobs took place in the falling-rate period. The maize cobs dried in the STD were cleaner than those dried under OSD.

##### 7.1.2 To carry out thin layer drying of maize cobs and finding an appropriate mathematical model

(i) Overall, the mathematical modeling equation which best fitted the drying curves was found to be Midilli et al. All models had a coefficient of determination above 0.9.

##### 7.1.3 To compare the presence of Aflatoxins levels in maize dried by Solar Tunnel Dryer and Open-Sun Drying

(i) Aflatoxins concentration levels were found to be below the acceptable levels according to Zambia Bureau of Standards requirements for samples of maize meal obtained from maize dried in the STD (8.37 ppb) and that taken from partially field

dried maize which was directly stored, that is, SFF (8.63 ppb). The only sample which had Aflatoxin concentration levels above that recommended by the Zambia Bureau of Standards (10 ppb) was that obtained from the control experiment, that is, OSD (11.57 ppb).

(ii) It should be noted that depending on whether the maize is meant for further processing to make feedstuffs, the allowable concentration levels America range from 100 ppb to 300 ppb.

#### **7.1.4 To evaluate the performance of the chimney on the natural convection dryer**

(i) The solar chimney always had a positive temperature rise above ambient temperature allowing for air to exit the dryer. The mean temperature values recorded in the 3 experiments were 8.2 °C, 14.9 °C and 3.6 °C respectively.

(ii) Values of buoyant pressure recorded were all positive and were as follows: 0.246450703 Nm<sup>2</sup>, 0.44858892 Nm<sup>2</sup> and 0.108192724 Nm<sup>2</sup> respectively.

### **7.2 Recommendations**

The following are the recommendations drawn from this study:

(i) Based on this investigation, to attain temperatures higher than the collector and drying chamber in the chimney, an investigation can be carried out with a tilted chimney to improve solar absorption.

(ii) Insulation should be used in parts where the dryer is connected to other parts to retain more heat in the dryer.

(iii) This dryer should be used for other products to see how it performs.

(iv) By engaging the Ministry of Agriculture, the use of the dryer can be tested with small-scale farmers so that they can improve their drying efficiency of agricultural produce.

### **7.3 Closing remarks**

The conclusions and recommendations have been given in this Chapter.

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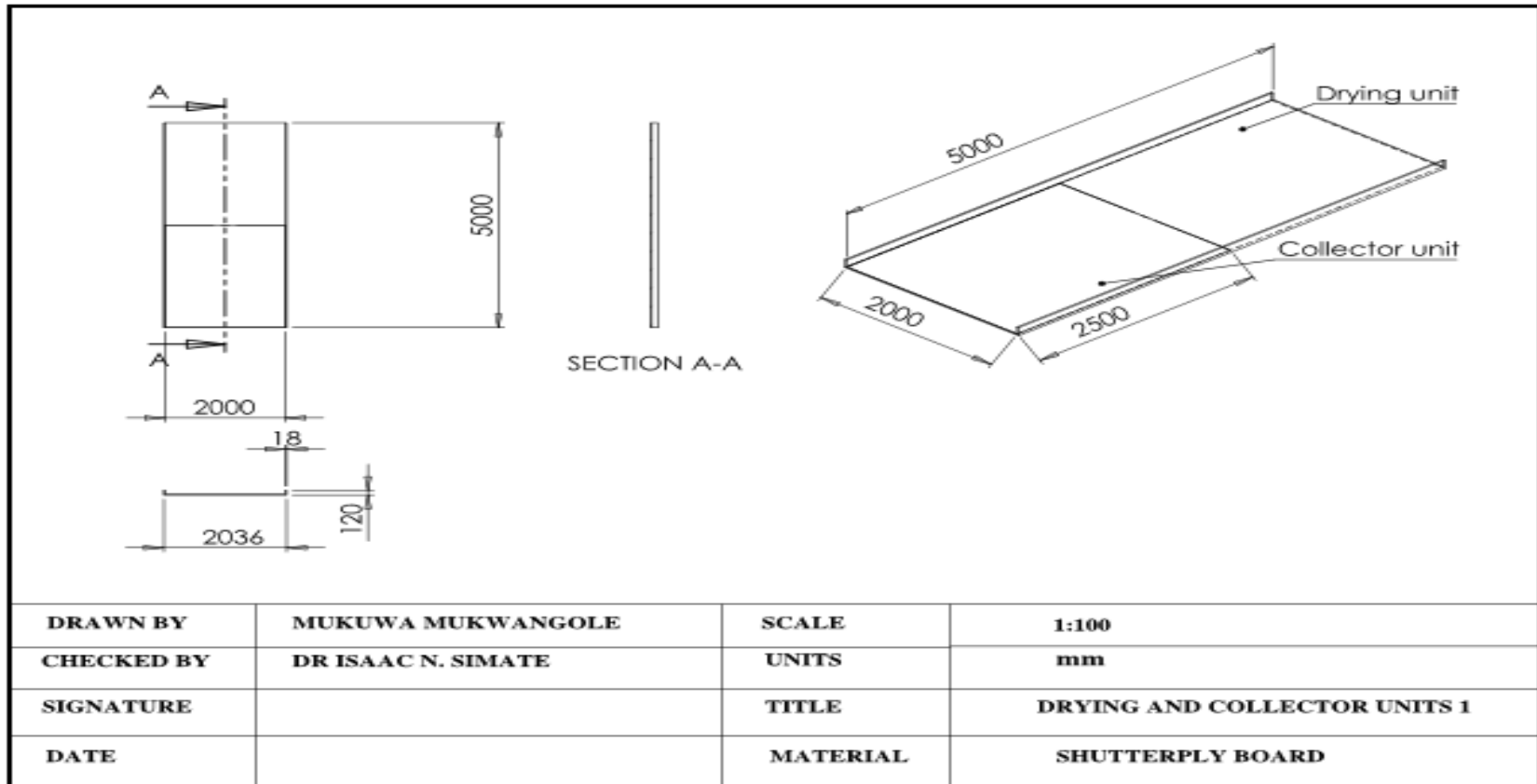
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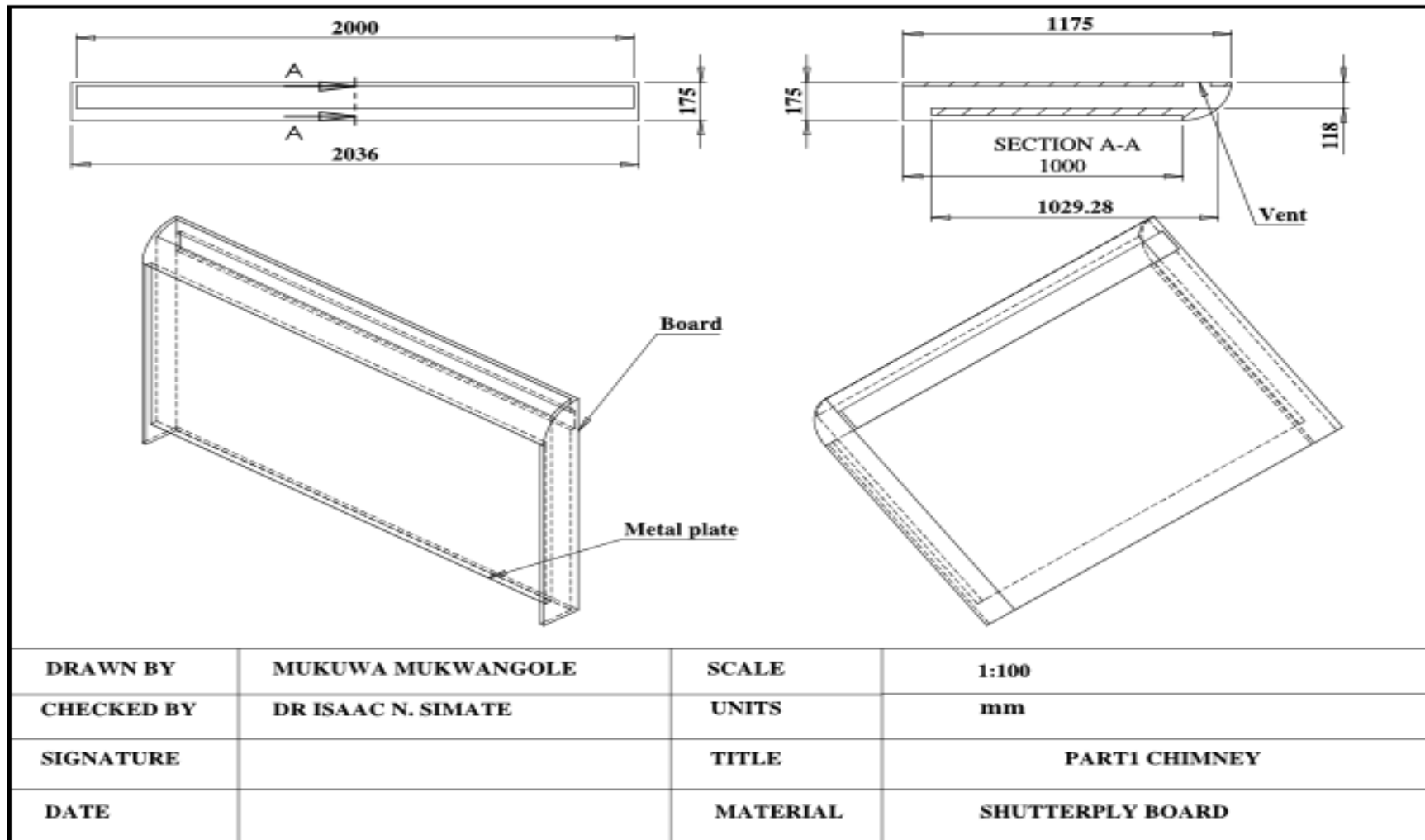
**Appendix I: Averages of meteorological data used for design of dryer**

<b>Date</b>	<b>Air Temp. (avg) [°C]</b>	<b>Air Temp. (min) [°C]</b>	<b>Air Temp. (max) [°C]</b>	<b>Wind Speed (vc avg) [m/s]</b>	<b>Humidity (avg) [%]</b>	<b>Solar Irradiance (Jain) [MJ/m2]</b>
<b>Jan-16</b>	23.3613	19.3226	28.6097	1.67419	73.2742	20.51774194
<b>Feb-16</b>	22.9276	19.0655	28.3034	1.23103	81.6172	19.90310345
<b>Apr-16</b>	20.51	16.23	25.79	2.02333	74.3667	19.13466667
<b>May-16</b>	18.0032	13.3581	23.9742	2.34516	63.1129	18.64193548
<b>Jun-16</b>	16.38	10.7433	22.9433	2.12	61.1133	17.66966667
<b>Jul-16</b>	16.8452	11.4645	23.1258	2.2129	56.1516	16.65774194
<b>Aug-16</b>	19.3419	13.4742	26.0355	2.56774	47.1484	19.66483871
<b>Sep-16</b>	23.5867	17.3567	30.4633	2.50333	35.29	21.65066667
<b>Oct-16</b>	26.4452	20.1806	33.2097	2.34194	34.4355	24.93677419
<b>Nov-16</b>	24.84	19.7233	30.87	1.87333	55.91	21.18233333
<b>Dec-16</b>	22.5	18.3611	28.1722	1.44444	75.1778	19.925
	<b>21.3401</b>	<b>16.2982</b>	<b>27.4088</b>	<b>2.03067</b>	<b>59.7816</b>	<b>19.98949719</b>

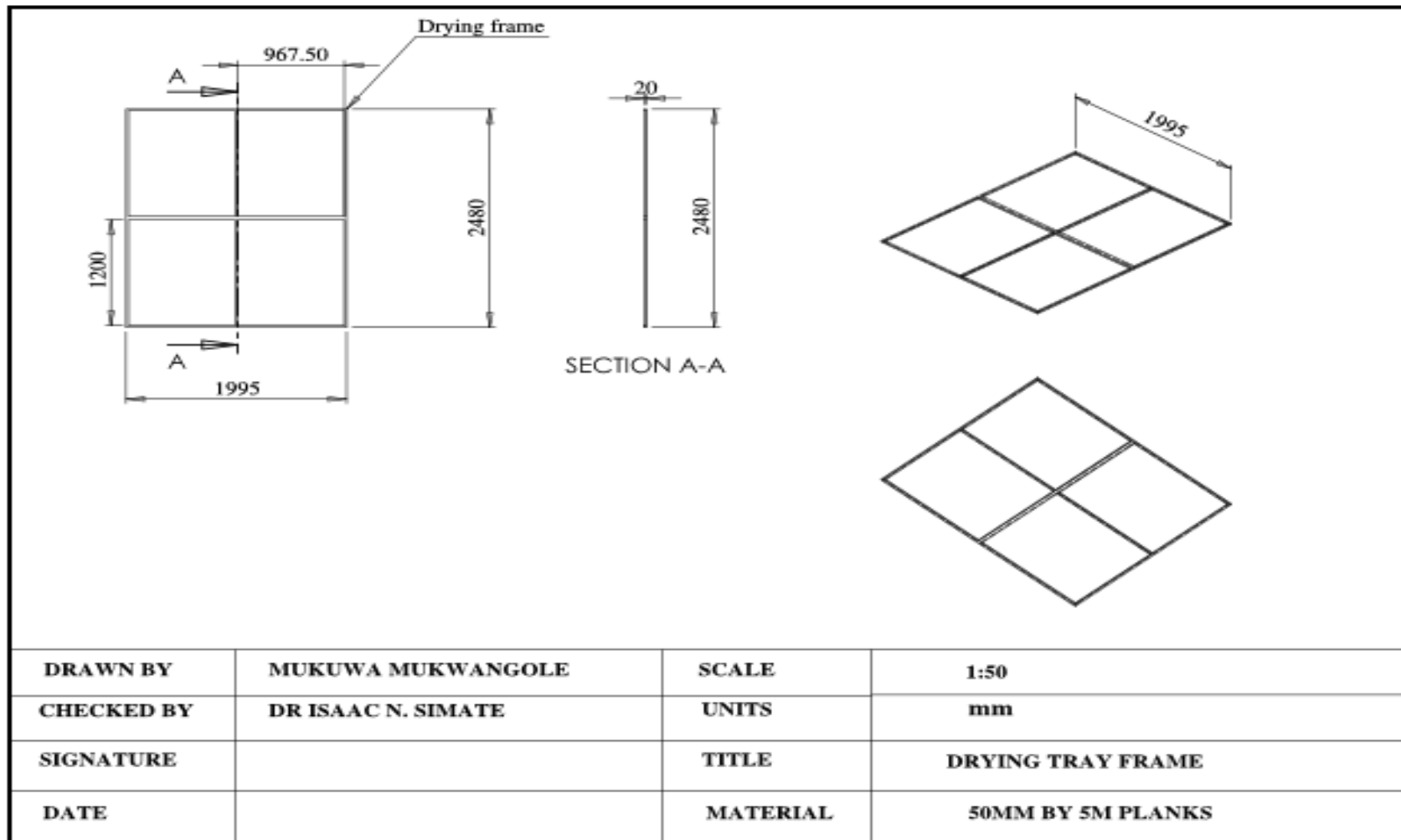
## Appendix II: Collector and Drying Units



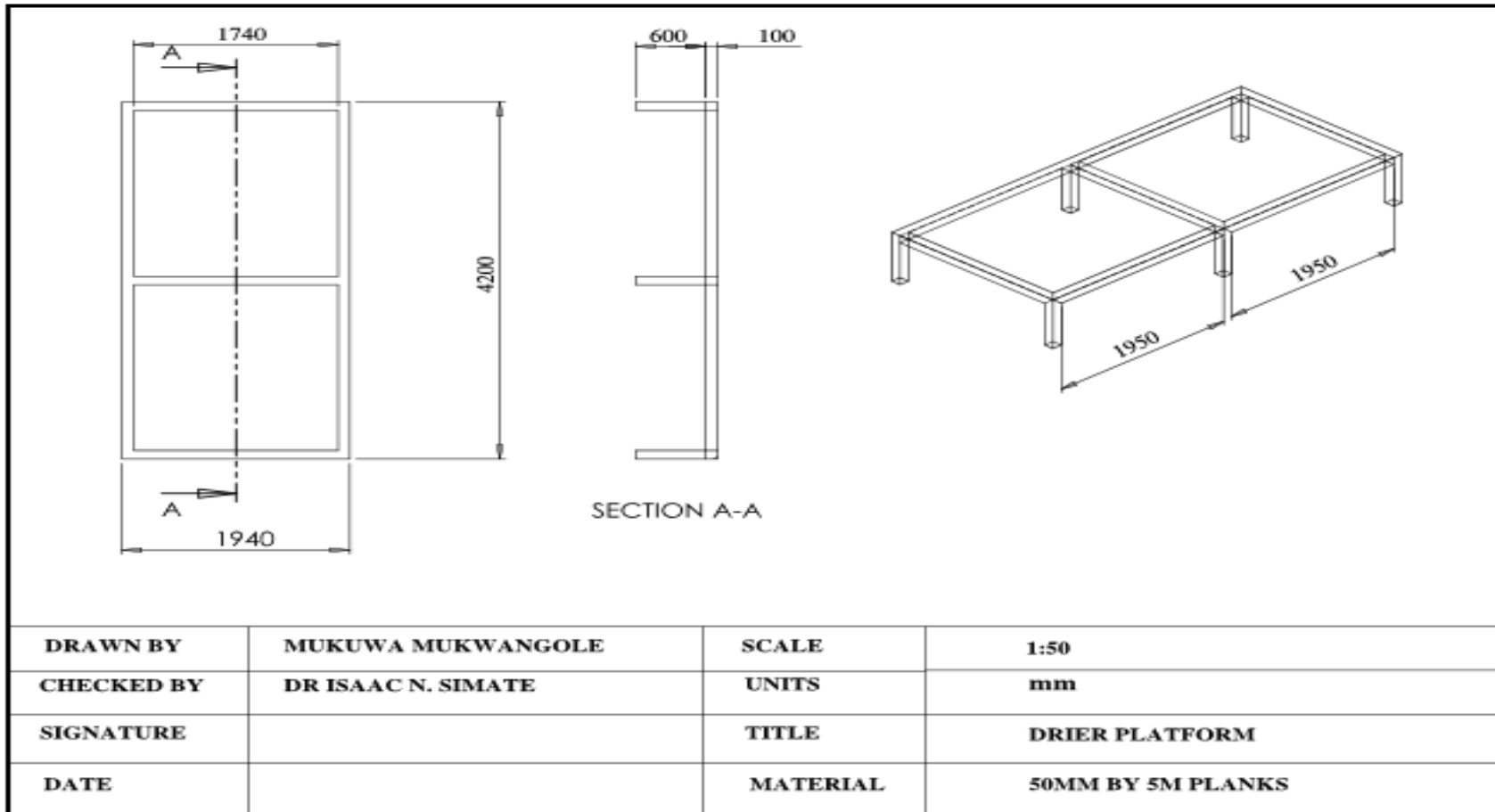
### Appendix III: Chimney Unit



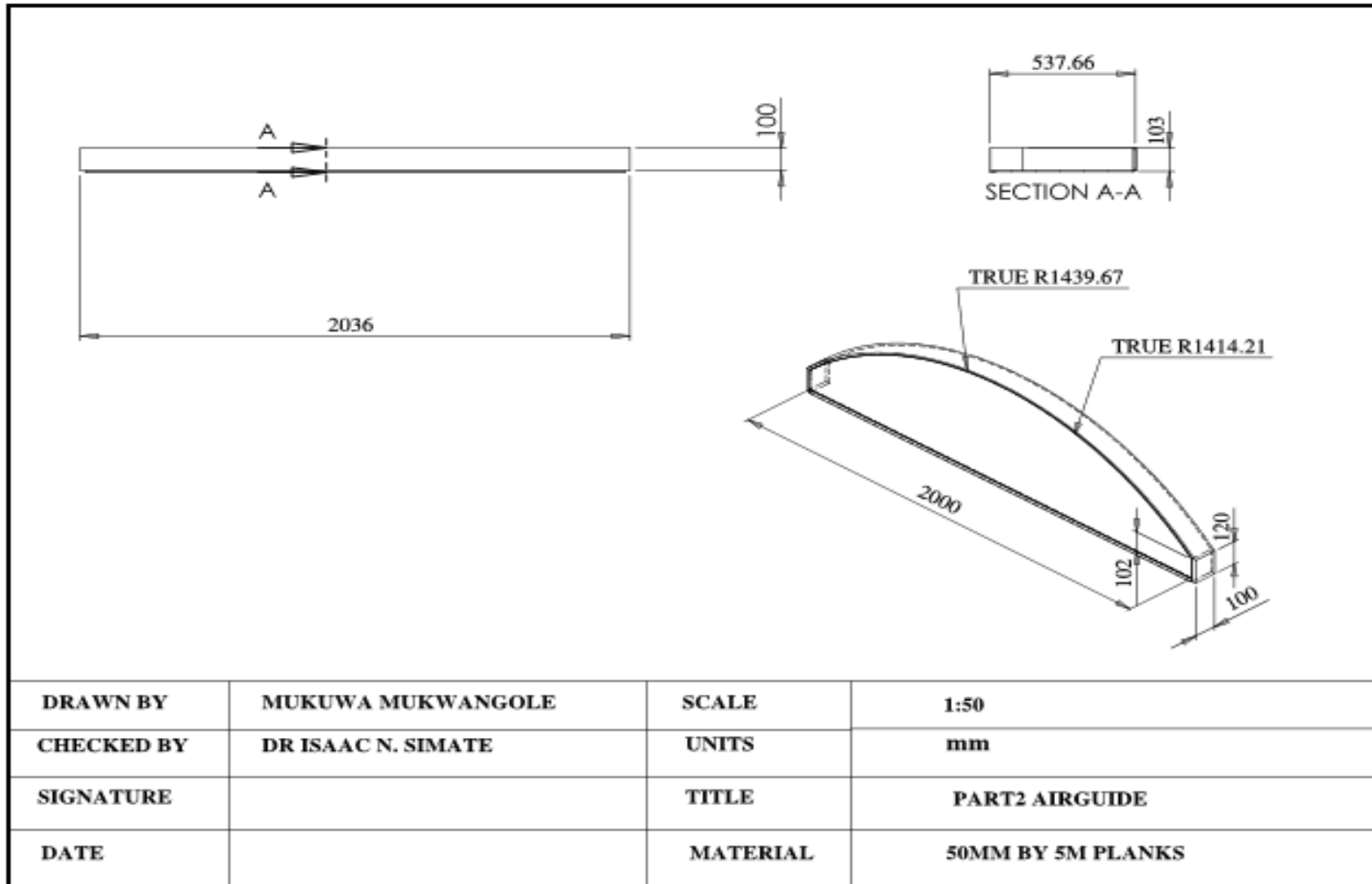
### Appendix IV: Drying Tray Unit



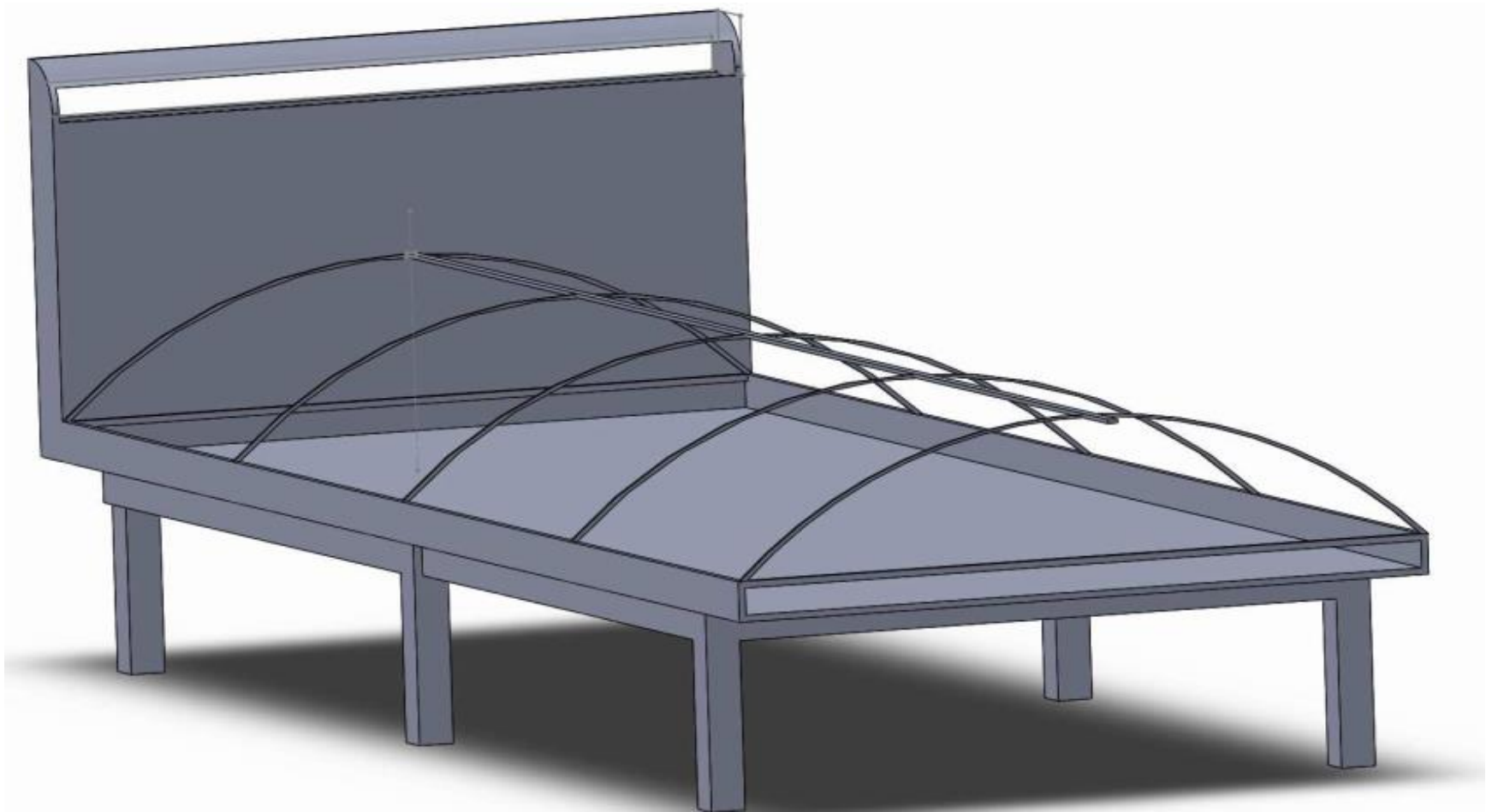
## Appendix V: Dryer Platform



### Appendix VI: Air Guide



**Appendix VII: Model View of Dryer**



### Appendix VIII: Solar Tunnel Dryer - List of Materials

Quantity		Size
1	Shutter ply board (18mm thick) - Base plate for collector unit	2500*2000*18 (mm <sup>3</sup> )
4	Shutter ply board ( 18mm thick) - Side plates for collector and drier units	2500*102*18 (mm <sup>3</sup> )
1	Shutter ply board (18mm thick) - Base plate for drying unit	2500*2000*18 (mm <sup>3</sup> )
1	Shutter ply board (18mm thick) - Rear part of chimney	1175*2000*18 (mm <sup>3</sup> )
2	Shutter ply board (18mm thick) - Side plates of chimney	175*1000*18 (mm <sup>3</sup> )
6	Planks (50mm*50mm*5000mm) - Stands of platform	100*100*600 (mm <sup>3</sup> )
4	Planks (50mm*50mm*5000mm) – Sides of platform (length)	2100*100*100 (mm <sup>3</sup> )
3	Planks (50mm*50mm*5000mm) - Sides of platform (width)	1940*100*100 (mm <sup>3</sup> )
2	Galvanised iron (3mm thick) – For air guide and chimney collector	2000*1000*3 (mm <sup>3</sup> )
2	Wire mesh – For placing on drying tray frame	2100*1940 (mm <sup>2</sup> )
1	1 litre Black paint for absorber plate	
1	1 kg nails	
1	Industrial staples	
1	500ml wood glue	
1	Ultra violet polythene plastic sheet	6000*3000 (mm <sup>2</sup> )