INFLUENCE OF TEMPERATURE, AIR FLOW RATE AND SLICE THICKNESS ON EGG DRYING RATE AND PROTEIN CONTENT UNDER FORCED CONVECTION

MECHA PETER

A thesis submitted to the Graduate School in partial fulfilment for the requirements of Master of Science Degree in Agricultural Engineering of Egerton University

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DECLARATION AND RECOMMENDATION

Declaration

I hereby declare that this Thesis is my original work and to the best of my knowledge has not been presented for an award of a degree in this or any other university.

Signature………………………. Date……………………

Mecha Peter

BM11/14139/15

Recommendation

This Thesis has been presented with my recommendation as a university supervisor.

Signature……………………… Date……………………

Prof. Daudi M. Nyaanga

Dept. of Agricultural Engineering

Egerton University

P.O. Box 536-20115 Egerton University, Kenya.

This Thesis has been presented with my recommendation as a university supervisor.

Signature…………………. Date...............................

Dr. Musa R. Njue

Dept. of Agricultural Engineering

Egerton University

P.O. Box 536-20115 Egerton University, Kenya.

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DEDICATION

This Thesis is dedicated to:

To my wife Bathsheba; Son Zablone for their patience and moral support during the period of my studies.

To my father Mecha, late mother Joyce, late brother Job and Sister Alice for denying themselves the comfort of life for the sake of my education.

To sister Evaline, Linet brothers Daniel, Elijah and Isaac for motivating me during my studies. May God’s blessings be upon you all.

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ABSTRACT

The availability of egg products for consumption is hindered by spoilage and breakages during processing. Forced convection drying serves as one of the methods of solving these challenges. However, the influence of temperature, airflow rate and slice thickness on forced convection drying of eggs is inadequately documented. Therefore, drying of eggs was investigated under forced convection process. The mode of airflow and the food material was the continuous concurrent type. Raw eggs were boiled at 90°C for 17 minutes to harden them. The hardened eggs were deshelled and cut into 10 mm thick slices without separating the egg yolk and egg white. Forced convection drying of sliced hardened eggs was done at thicknesses of 10 mm, 20 mm and 30 mm. Drying temperatures were set at 35°C, 40°C and 45°C. Airflow rates were set at 0.09 m³/s, 0.12 m³/s and 0.15 m³/s. Protein content for each sample was determined using Kjeldahl method. L_9 Taguchi orthogonal array technique was used to determine the optimal combination of airflow rate, drying temperature and egg slice thickness that gave the highest drying rate and protein content. Nine thin layer-drying models were fitted to the experimental data to determine the model that predicted drying process with minimal variations between experimental and predicted results. An analysis of variance at 5% level of significance showed that air drying temperature had significant influence on the drying rate and protein content. The drying rate increased with increased air drying temperature. The drying rate increased from 0.67 g/g min to 0.75 g/g min with rise in temperature from 35°C to 45°C respectively. Protein content dropped from 54.6% to 47.5% with increase in temperature. Increasing drying airflow rate increased drying rate from 0.67 g/g min to 0.76 g/g min at 0.09 m³/s and 0.15 m³/s. The protein content decreased from 54.4% to 48.3% at 0.09 m³/s and 0.15 m³/s. Increasing airflow rate had significant influence on protein content ($p<0.05$). Thickness increment led to decrease in drying rate from 0.72 g/g min to 0.68 g/g min at 10 mm and 30 mm. Lower slice thickness had lower protein content of 47.9% while the highest thickness had protein content of 53.8% due to high heat transfer in the lower thickness that thermally affect proteins. Increasing thickness had insignificant influence on protein content ($p>0.05$). The optimal combinations for drying rate were slice thickness of 10 mm, flow rate of 0.15 m³/s and temperature of 45°C. Slice thickness of 30 mm, airflow rate of 0.15 m³/s and temperature of 35°C were the optimal combinations for protein content. Page, Modified Page, and Aghbashlo *et al.* were found suitable for predicting drying processes of boiled eggs. However, Page model was most superior of the three with the highest R^2 of 0.9991, lowest x^2 and RMSE of 0.0001 and 0.0012 respectively.

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ABBREVIATIONS

C.P	Crude Protein
db	Dry basis
DOF	Degree of freedom
kPa	kilopascal
kW	Kilowatt
MR	Moisture ratio
P.F	Protein factor
S/N	Signal to noise ratio

LIST OF ACRONYMS

ANOVA	Analysis of variance
ASAE	American Society of Agricultural Engineers
MoEST	Ministry of Education Science and Technology
Mol.	Molecule
OA	Orthogonal Array
PID	Proportional Integral Device
RMSE	Root Mean Square Error
UNIDO	United Nations Industrial Development Organisation
subscripts	
exp.	Experimental
pre.	Predicted

LIST OF SYMBOLS

R^2	Coefficient of determination
L_9	Nine row experimental orthogonal array
$\bar{y}$	Average of the samples
y^2	Square of individual samples
%	Percentage
<	Less than
>	Greater than
Δt	Change in time (min)
$\sum$	Summation
$\leq$	Less than or equal to
$\geq$	Greater than or equal to
©	Copy right
°C	Degree centigrade
a, b, c	Drying coefficients
d	*dry*
e	*equilibrium*
f	Factor of standard hydrochloric acid (=1)
g	Grams
i	Initial
i	*instantaneous*
K	Kelvins
k, k_1, k_2, n	Drying constants
L	Half-length
M	Moisture content
N	Number of observations
N	Nitrogen
N_s	Normality of standard hydrochloric acid
o	*initial*
R	Universal gas constant (8.3143 $kJ/mol.K$)

S	Weight of sample taken for protein analysis
s	*standard*
	Subscripts
T	Absolute temperature (*K*)
t	*time*
V	Volume
V1	Sample titre
V2	Blank titre
W	Mass (g)
w	*wet*
Z	Number of constants in an equation
π	pi
χ^2	Reduced chi-square

CHAPTER ONE
INTRODUCTION

1.1 Background

The global demand for eggs and egg products is increasing especially in most of the developing countries with Kenya included (Magdelaine, 2011). Responding to these demands poses many challenges especially in storage and transportation of eggs and their products. These challenges are mainly in production, preservation, storage, and transportation process. These challenges are mostly due to lack of sustainable methods of preserving egg products and the problems associated with bulky and brittle nature of eggs making it hard to transport. These difficulties are further worsened because about 80% of agricultural production in Kenya is based in rural areas as reported by Kituu (2012). This concentrated rural production makes it hard to transport eggs to towns where most consumers reside. Eggs normally gain a lot of demand because they are one of the most versatile and near perfect foods in nature. They are rich in protein, amino acids, vitamins and most mineral substances.

The yolk and white components are all of high biological value and are readily digestible. Kumaravel *et al.* (2011) reported that beside milk, eggs are the best source of proteins. They are also among the most consumed foods worldwide and important commodities in international trade (Darvishi *et al.*, 2012). Chicken egg, whole and hard-boiled, for instance contains 52.1% protein content in dry basis (db), 10.6 g/100g fat, 1.12 g/100g carbohydrate and 647 KJ/100g energy according to Eke *et al.* (2013). All these vital properties raise demand for eggs especially for people who need special nutrition. Therefore, this calls for new techniques of processing eggs in a cheaper and easily affordable process. Forced convection drying of eggs will add to us achieving food security globally. Additionally, there will be a positive improvement towards sustainable development goals (SDG) and vision 2030 in Kenya.

One method of preserving eggs is to increase their shelf life through drying. Drying eggs would also ease transportation. Drying products under controlled conditions removes water from foods by evaporation or by sublimation. The process is affected by air temperature, humidity and airflow rate among other factors (Fellows, 2009). Bhandari *et al.* (2013) found out that drying of eggs leads to three times reduction in volume of raw eggs due to removal of moisture from the eggs. This justifies dehydration as one of the solutions to the current problems of egg processing and transportation. The current processing methods like spray drying use high temperature that affects the quality of eggs. Additionally, portions of powder are blown away during spray drying process. Contact heating in ohmic heating process lowers the quality of eggs. Freeze and foam-mat drying are energy and time intensive while direct solar drying does not allow control of the drying parameters. Boiling eggs before drying and grinding them to get powder offers a solution of reducing post-harvest losses. Additionally, forced convection drying of eggs can reduce processing time as compared to freeze and foam-mat drying.

Egg powders are widely used in food processing including emulsification, adding colour, tenderness and flavour. Bhandari *et al.* (2013) reported that egg powders are highly stable product with shelf life of over two years, almost fat free, microbiologically safe and reduced volumes. Egg powders are efficiently functionalized (improved binding, coagulation, emulsification, and aeration) by heat treatment into high foam or high gel powders. However, majority of these methods are inadequately available hence making it expensive to apply. Consequently, there is need of improvising a readily available cheaper method and scientific knowledge to solve preservation, storage and transportation challenges facing egg industry.

One way of drying hardened eggs is through forced convection. It has the advantages of increasing drying rate and controlling drying process through regulation of temperature and airflow rate is easier. Therefore, it can be used in drying eggs and giving optimum conditions for the process. Most of the researches done on the aforementioned methods have little information on egg drying process parameters. This includes drying temperature, airflow rate and slice thickness in addition to their influence on drying rate and protein content of eggs.

1.2 Statement of the Problem

Even though eggs and their products are cheaper compared to meat and milk products with a better source of foods with most ingredients, their availability is hindered by spoilage and breakages during transportation. Dependence on spray drying, foam-mat drying, belt drying and ohmic heating methods of preservation and transportation is expensive and inadequately available in most developing countries. Forced convection drying is one of the available and feasible methods of these challenges. Besides providing the solution, some of its process parameters may affect drying rate and protein content of dried eggs. However, the actual influence of temperature, airflow rate and slice thickness on forced convection drying of eggs is inadequately known. The optimal drying conditions for predicting thin layer drying of eggs with minimal changes in quality during drying has not been adequately documented. Consequently, there is lack of known thin layer model that satisfactorily gives the minimum deviations between experimental and predicted moisture ratios. This poses more challenges in predicting drying trend of eggs that can give more information on how to design the dryer.

1.3 Objectives

The broad objective of this study was to determine the influence of airflow rate, drying temperature, and slice thickness on egg drying rate and protein content using a forced convection drying system.

The specific objectives were to:

i. Determine the influence of airflow rate, air temperatures and egg slice thickness on drying rate and protein content of eggs in a forced convection dryer.
ii. Evaluate and optimize egg-drying process under forced convection drying.
iii. Test and validate selected thin layer drying models for egg drying under forced convection.

1.4 Research Questions

i. How does drying airflow rate, temperature and egg slice thickness influence the drying rate and protein content of eggs?
ii. What is the optimal combination of airflow rate; air temperature and egg slice thickness that should be used for the forced convection egg dryer?
iii. Which drying model gives the lowest variation between the experimental and predicted egg drying rates and protein content?

1.5 Justification

Since eggs' powder provide a near complete solution to bulkiness, fragility, and perishability of eggs, drying serves as one of the appropriate options to the challenges mentioned above in the problem statement. Unlike the common method of drying eggs (spray drying, freeze drying, foam-mat drying, ohmic heating and belt drying), forced convection drying of eggs can provide another alternative technology for drying eggs. Forced convection drying of eggs can also provide control of drying process parameters. One of the ways of finding eggs drying conditions is by optimising the process parameters to give a combination that can speed up drying rate as well as having high protein content. By varying the process conditions, one is able to determine optimal conditions that can in turn be used to find the model that describes eggs' drying process by giving minimum deviation between experimental and predicted moisture ratios. This would result into development of an alternative and efficient process for drying eggs to desired final moisture content and protein content using forced convection system. The product formed would be convenient to handle, store, and easily transportable due to reduced bulkiness and fragility; and as well mix with other bakery raw materials. The optimal conditions and appropriate model found could be used to develop a forced convection dryer specifically for eggs.

1.6 Scope and limitations

This study used an experimental forced convection egg dryer whose temperature was regulated from 35^{o}C to 45^{o}C using 1.8 kW heaters and 3 sets of pulleys to vary the speed of centrifugal fan hence varying airflow rate from 0.09 m^3/s to 0.15 m^3/s. The focus was on drying process of 10 mm, 20 mm and 30 mm boiled whole egg slices. The eggs used were grade 1 from hybrid chicken. The study sought to optimize drying process of hardened eggs under the system in terms of protein content and drying rate. Protein was chosen since it was the major nutritional component in eggs. The drying process was evaluated using hardened egg slices and focused on influence of egg slice thickness, airflow rate and drying air temperature on drying rate as well as protein content.

This study was limited to sliced boiled egg studied wholly without separating egg yolk and the egg white part. In addition, lack of equipment used for testing various egg components limited the number of qualities investigated in this study. The various egg components/properties not investigated included colour, instantaneous protein content, storability, and digestibility. They were treated as negligible variables affecting drying process and their effects assumed insignificant.

CHAPTER TWO
LITERATURE REVIEW

2.1 Forced Convection Drying

Unlike natural convection, which occurs at an ambient room air conditions without an external source of motion, forced convection drying system requires mechanical or electrical powers to provide airflow. Sami *et al.* (2014) reported that the system saves time, occupies less area, improves product quality and hygiene, makes the process more efficient and protects the environment. This drying technology involves a means of generating hot air to dehydrate substances with certain percentage of moisture in their composition. This results into a mass transfer of water molecules in the process of drying operation.

Different successful approaches have been used to produce hot air such as electrical filaments, burning of fossil fuel, chemical adsorption and desorption among other sources of energy (Kareem *et al.*, 2016). Therefore, since there is influence of temperature gradient and concentration gradient on forced convection drying in the aforementioned approaches, then drying under forced convection is a heat and mass transfer process. In a forced convection system, control of drying process is simpler. The drying chamber is separated from heating chamber hence facilitating the loading, unloading, and handling of the product. However, since drying chamber is opaque, this system allows drying of convenient products that may lose their quality of appearance by a direct exposure to the source of energy. According to Finck-Pastrana (2014), the second less apparent disadvantage is evaporation of same amount of moisture using more mass of air at higher temperatures than in the case of direct dryers. However, despite the demerits mentioned, forced convection drying increases the amount of air and temperature hence increased drying rate.

2.1.1 Continuous flow drying systems

Maier and Bakker (2002) described three major continuous-flow drying systems employed in industry as cross-flow, mixed-flow and concurrent-flow. This classification was based on the directions the product and air moved through the dryer. In a cross flow dryer, air and product move perpendicular to each other, while in a concurrent-flow dryer they move in parallel. In mixed flow dryer, part of the airflow in (concurrently or parallel), against (counter), and perpendicular to the product being dried. These patterns have a significant effect on drying capacity, energy efficiency, product quality, and product temperature. In concurrent-flow, the product being dried is directed into the hot air entering the dryer and both pass through the chamber in same direction.

2.1.2 Merits and limitations of different drying systems

In concurrent type, there is rapid initial drying, little shrinkage, less heat damage to food and no risk of spoilage as the major advantages. Conversely, low moisture content is difficult to achieve as cool moist air passes over dry food. This is because moisture removal from the product reduces concentration gradient making mass transfer to be less as drying airflows in same direction as material. Thus, it takes more time and energy to dry the material. The concurrent flow drying are typically chosen for heat sensitive products as the particle temperature remains lower than in counter-current case (Bayly *et al.,* 2004). The counter current drying has economical use of energy and low final moisture content as hot air passes over dry food. The system is also beneficial for materials that have internal moisture retention and require higher heat and a longer drying cycle to draw out both the bound and unbound moisture from the drying product as argued by Thunman and Leckner (2003).

Bayly *et al.* (2004) recounted that in drying of more robust materials, the counter current process offers higher thermal efficiency and can lead to different, in some cases desirable, product characteristics. This makes drying a faster process. However, counter current has food shrinkage, possible heat damage and risk of spoilage from warm moist air meeting wet food as reported by Mujumdar (2014). The risk of spoilage from warm moist air interacting with wet food is not applicable in thin layer drying because humidity is assumed constant during drying process. However, shrinkage and possible heat damage may occur. Since there is possibility of heat damage, the drying parameters like temperature, airflow rate and slice thickness should be controlled to minimise these outcomes. Once this control is done, drying of sensitive products like hardened eggs become possible.

Centre exhaust drying has combined benefits of parallel and counter current drying but less than that for cross flow dryers. They have the limitation of being more complex and expensive than single-direction airflow. For the cross-flow type, there is flexible control of drying conditions by a separately controlled heating zones, giving uniform drying and high drying rates. Mujumdar (2014) noted that the drying system is more complex and expensive to buy, operate and maintain. The summary of various types of drying systems and schematic process for food and airflow directions is shown in Table 2.1.

Table 2.1: Merits and limitations of different types of drying systems

Type of airflow	Advantages	Limitations
Concurrent Food → Air flow →	• Rapid initial drying • Little shrinkage • Low bulky density • Less heat damage to food • No risk of spoilage	• Low Moisture content difficult to achieve as cool moist air passes over dry food
Counter current Food → Air flow ←	• More economical use of energy • Low final moisture content as hot air passes over dry food	• Food shrinkage and possible heat damage • Risk of spoilage from warm moist air meeting wet food
Centre exhaust Food → Air flow → ↑ ←	• Combined benefit of parallel and counter current dryers but less than cross flow dryers	• More complex and expensive than single direction air flow
Cross flow Food → Air flow ↑↓	• Flexible control of drying conditions by separately controlled heating zon es, giving uniform drying and high drying rates	• More complex and expensive to buy, operate and maintain

Adopted from: (Mujumdar, 2014)

2.1.3 Thin layer tray dryers

Tray dryers constitute an important family of convective dryers, where the drying medium is hot air or combustion gases coming from a given heater. They are adaptable to the drying of almost any material that can be put in a tray as reported by Kiranoudis *et al.* (1997). They consist of insulated cabinets fitted with shallow mesh or perforated trays, each of which contains a thin (20-60 mm deep) layer of food. Hot air is circulated through the cabinet at airflow rates of 0.5-5 m^3/s. The fan sucks fresh air through the electric heaters and then pushes the heated air through the food trays as illustrated in Figure 2.1. In this case, the air is heated indirectly. Screens filter out any dust in the drying air. If the designs have perforated trays, the air is directed up through them; otherwise, it passes across and between the trays. The air is exhausted to the atmosphere after one pass rather than being recirculated within the system (Mujumdar, 2014). However, in recirculating designs, the moisture-laden air after evaporating water from food has to be dried before being recirculated or else it would become saturated and further drying of food would stop. In such a case, passing it through a desiccant such as a bed of silica gel or condensing moisture out by passing the moist air over cold plates or coils could dry the air. Thermometers are installed with sensitive elements directly in the main air current approaching the drying trays and air current leaving trays (Mujumdar, 2014). One of the problems encountered is to supply same drying rate at all positions within the tray dryers. This is solved by using airflow rate controllers.

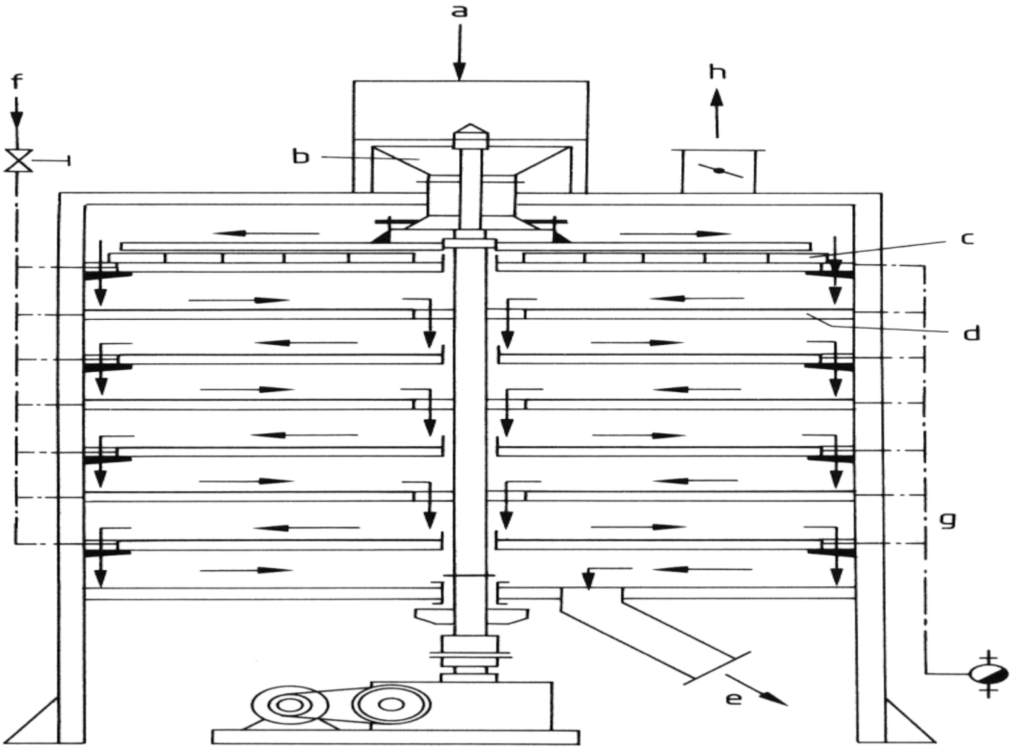

Figure 2.1: Tray dryer

Adopted from: (Mujumdar, 2014)

Key: *a) Moist solid loading; b) Rotating tray feeder; c) Rakes (only drawn for topmost level); d) Heated tray; e) Product discharge; f) Steam; g) Condensate; h) Exhaust*

The other problem is fast drying of food in the position where air first enters the system and slow drying of food in the other position. Thus, additional heaters and fans may be placed above or alongside the trays to increase drying rate. Tray dryers are used for small-scale production (1-20 tonnes) or for pilot-scale work. They are commonly used to dry fruit and vegetable pieces. Depending upon the food and desired final moisture content, drying time can be between 10 to 20 hours (Mujumdar, 2014).

2.2 Egg drying

2.2.1 Importance of egg drying

According to Bhandari *et al.* (2013), egg powders are functional ingredients which offer enhanced technological properties compared to liquid egg products. Moreover, powders reduce transport and storage costs, are easy to handle in a safe manner, are not susceptible to bacterial growth and enable precise dosing used in formulation. Egg powders are thus used in many segments of food industry and are specifically designed for customers' formulations.

Eggs powders are formulated specifically for the needs of users. For example, the feed of laying hens can be designed to enrich eggs with specific colouring agents or essential fatty acids. It is thus possible, with quite a small number of hens, to collect eggs with optimal concentration of any target component and store them in a short term. They are then dried in to obtain homogeneous batch of powder that has a shelf life of over a year. Eggs powders are also used in the production of organic, free range and contractual products (Bhandari *et al.*, 2013). This implies that egg powders play a crucial role in the control of national and international eggs markets. As a result, better post-harvest technologies on eggs need to come into place to foster this international trade.

The average protein content of eggs is 52.1% (db) and the moisture content is 75.8% as reported by Bradley (2010). This means that egg consumption provides the major source of proteins to human beings and thus need more processing techniques to assure as of its availability to all regardless of the season and place. High moisture content makes eggs to spoil faster and is bulky during transportation. The consumption of eggs and its products varies with seasons as farmers sometimes over-produce. Eggs drying enables producers to delay eggs consumption and to supply markets with ingredients at the time of need (Bhandari *et al.*, 2013). This means that poultry farmers can produce and store more eggs in dried form and supply when demand is high. Transportation of dried eggs to needy areas is convenient since the risks of breakage are not there.

2.2.2 Methods of drying eggs

Drying of most agricultural products is advantageous in terms of creating a smaller space for storage, longer shelf-life, lighter weight and storability under ambient temperatures and other conditions (Chayjan *et al.*, 2013). The processes employed in the production of dried eggs include pan-drying, foam drying, freeze-drying, and spray drying. In pan drying, flake-type eggs produce white products.

In foam drying, glucose-free and concentrated eggs white is placed on plates in room at temperature of 54°C in which slow concentration and drying occurs without coagulation. A vitreous product is obtained, containing between 12% and 16% moisture; this is ground to different sizes to meet customer requirements. This product needs at least 24 hours to rehydrate. It is mainly used for aerated confectioneries as reported by Bhandari *et al.* (2013). This type of drying takes more time hence costlier and unreliable.

In freeze drying process, the material is first frozen completely to convert moisture into ice. After complete freezing, the material is placed inside a drying chamber, where pressure is reduced to create vacuum. After the required amount of vacuum is reached, the temperature of shelf is gradually raised to supply the necessary latent heat of sublimation. When the triple point conditions are reached and maintained, ice is directly sublimated. The freeze drying takes advantage triple-point property of water and works on the same principle during drying (Muthukumaran *et al.*, 2008). However, according to Bhandari *et al.* (2013), the cost of freeze drying is high due to high latent heat requirements and time needed to reach triple point of water, thus limiting its commercial applications.

Foam-mat drying is an old technology used to process hard-to-dry materials, obtain products of desired properties like favourable rehydration, controlled density and to retain volatiles that otherwise would be lost during drying of non-foamed materials. The principle is to dehydrate a liquid concentrate along with or without foam stabilizer in a foam-mat form. Foaming is performed by injecting a gas such as carbon dioxide, nitrogen or air into the liquid before drying process takes place. This is common with spray drying, pan drying and belt drying. Foaming is also done before conventional freeze-drying and microwave drying of frozen foams. Compared to spray drying, foam-mat drying requires less time, less energy, less production costs with no need for concentration (Bhandari *et al.*, 2013).

In spray drying, the more frequently used method (Ignário and Lannes, 2007), a liquid droplet is dried rapidly after being exposed to a stream of hot air. The small size of liquid droplets allows for very rapid drying and residence time of the material inside spray dryer is in the order of seconds. The dried material is separated from air in a cyclone separator. The drying rate and time required for drying depends on temperature of the droplet being dried. Heat can damage the product if it is in contact with high temperature drying air for long time. The denaturing of eggs yolk lipoproteins is a problem that is logically been related to poorer emulsifying properties (Ignário and Lannes, 2007).

The other method includes ohmic and Belt drying. Ohmic heating which is based on passage of electrical current through food product that serves as an electrical resistance. Heat is generated instantly inside the food resulting to drying of the product. The efficiency of ohmic heating is dependent on products' electrical conductivity. However, this method has a high influence on the colour of dried eggs as compared to conventional heating (Darvishi *et al.*, 2012). Belt drying is also another method mostly used in China to produce dried whole egg yolk and egg white solids. The liquid is spread as a thin film on a continuous aluminium belt moving through a hot air system. The dried foam produced by this method is then broken up into the desired granulation (Bhandari *et al.*, 2013).

2.2.3 Drying rate parameters for eggs in different dryers

Various researchers have reported different parameters affecting egg drying using different systems. For instance, Koç *et al.* (2011) used inlet (165–195°C) and outlet air temperatures (60–80°C) and the atomization pressure (196–392 kPa) as spray drying process variables. Spray drying process and conditions have influence on the gel texture that strongly depends on protein denaturation. Their investigation shows that outlet air temperature and atomization pressure had more effect than inlet air temperature on the properties of whole egg powder (Koç *et al.*, 2011). Katekhong and Charoenrein (2017) found that drying egg white using hot-air drying and storage especially at high temperature changes eggs' colour and protein conformation. These have contributed to protein aggregation that affected dried egg white's gel properties. This shows that the hot-air drying temperature of eggs is chosen carefully to minimize its negative effects.

In pan drying, each of the temperature range of 45^{o}C to 55^{o}C was used for a duration ranging from 30 to 48 hours. The result showed that both temperature and time had significant effect on solubility and coagulation time of the egg white powder (Nahariah *et al.*, 2018). In freeze drying of eggs, temperature and relative humidity are important parameters which produce changes in the properties of freeze dried egg powder during storage (Katekhong and Charoenrein, 2017).

In foam-mat drying, temperature range of 40-80°C, thickness of 4 mm with circle diameter of 70 mm and relative humidity range of 70-80% has been used. It was found that drying rate increased with increase in temperature and decrease in thickness (Djaeni *et al.*, 2015). Thirupathi *et al.* (2008) used temperatures of 60, 65 and 70°C and foam-mat thicknesses of 1, 3 and 5 mm and found that drying time of foamed whole egg powder is lower in l mm foam thickness at 60 minutes. This is when it was compared to 3 and 5 mm foam-mat thicknesses as 70 and 80 minutes respectively. The quality of the foam-mat dried whole egg powder at 60°C with 1 mm thickness retained more biochemical contents when compared to other drying temperatures and foam thicknesses. This shows that lower temperatures of drying egg under foam mat had better biochemical quality than higher temperature and thickness.

Iccier and Bozkurt (2011) used the temperature range of 4–60°C and the voltage gradient range of (20-30 V/cm) at 50 Hz for ohmic heating. They found that liquid whole egg exhibited higher degree of thixotropic index indicating the occurrence of protein denaturation at 60°C. This implies that temperatures lower than 60°C and lower voltage gradient were appropriate for better protein quality (Icier and Bozkurt, 2011). According to Darvishi *et al.* (2012), ohmic heating has high influence on the colour of egg samples as compared to conventional heating.

2.2.4 Drying parameters influencing protein content in agricultural products

The drying process normally has some effects on protein quality and composition of products especially protein from fish (Aberoumand, 2015). According to Zheng *et al.* (2005), excessive high drying temperature results to loss of protein in the leaves of alfalfa plant .On the other hand, air velocity offers opportunity to increase airflow rate without destroying the desired properties of the product. This shows that a lot of care is needed when apportioning drying parameter for agricultural products with eggs included. This is because the action of applying heat to a material in order to dry it does not merely remove the moisture but can also affect the nutritional qualities of the dried product.

Most agricultural products especially plant materials have their protein content increased with rise in drying temperature. This is due to the presence of microbes in the sample. The drying temperature and time has significant effect on the protein content with the effect of temperature on protein content being slightly lower than that of the drying time (Idah *et al.*, 2010).

Vujadinović *et al.* (2014) found that different heat treatment techniques have different effects on the state of animal proteins. Any drying parameter that would increase heat content indirectly causes denaturation of protein hence care is needed in selecting processing parameters. Akkouche *et al.* (2012) argued that depending on the extent of temperature and duration of the treatment, these changes can cause denaturation at the gelation or coagulation stage. The effect of heat was seen on some physico-chemical properties in egg white proteins such a sigmoidal evolution of transmittance and irreversible loss of solubility. Consequently, protein content of eggs is affected by process parameters that increases heat transfer especially if the materials are subjected to temperature for long time (Idah *et al.*, 2010).

2.3 Taguchi optimization technique

Athreya and Venkatesh (2012) reported that Taguchi method is a statistical approach developed by Taguchi and Konishi to optimize process parameters and improve the quality of manufactured components. The method is widely used and acknowledged by many statisticians especially in the development of designs for studying variation of parameters in a given process. For one to accomplish the best-anticipated outcomes there must be a careful selection of process parameters by categorising them into control and noise factors. The control factors must be made such that they nullify the effect of noise factors. The technique further involves identification of proper control factors to obtain optimum results for the process. Orthogonal Arrays (OA) are used to conduct sets of experiments that reduce time and cost of carrying out large amount of experiment. Results for these experiments were used to analyse data and predict the quality of components produced (Athreya and Venkatesh, 2012).

The technique, due to its superiority in reducing trials, has been widely used for optimising many industrial manufacturing processes as proved by Chen *et al.* (2011) in various manufacturing scenarios. Therefore, the technique can also be applied in optimising drying process of any agricultural products including eggs. This will give appropriate combination of the process parameters suitable for drying.

The technique is divided into three-stages: System design, parameter design, and tolerance design. System design, involves the input of scientific and engineering information needed for producing parts or coming up with process parameters. Contrary, the tolerance design helps to determine and to analyse tolerances about optimum combinations suggested by parameter design. Parameter design helps to obtain optimum levels of process parameters for developing the quality characteristics and determine product parameter values depending on optimum process parameters (Oktem *et al.*, 2007).

The Taguchi technique offers use of S/N ratio to identify quality characteristics applied for engineering design problems. The S/N ratio characteristics is divided into three steps: The smaller the better, the nominal the better, and the larger the better (Wu and Wu, 2000). Thus, S/N measures the quality based on reduction of variation during processing, while orthogonal array accounts for the number of experiments. Equation 2.1 is used when the desired characteristic is nominal while equation 2.1 is used for the smaller the better characteristics. For the larger the better, equation 2.3 is used to achieve the desired objective where, *n* is the total samples, *y* is the individual sample observation.

a) For the nominal the better;

$$S/N = 10 \log \frac{\bar{y}}{s_y^2} \qquad 2.\ 1$$

b) For the smaller the better;

$$S/N = -10 \log \frac{1}{n}\left(\sum y^2\right) \qquad 2.\ 2$$

c) For the larger the better;

$$S/N = -10 \log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \qquad 2.\ 3$$

2.4 Drying models

Drying of agricultural products is one of the main goals of preservation, transportation, and commerce. On the other hand, drying is a process with simultaneous heat and mass transfer. Food drying needs a lot of care and systematic design of the drying machine is needed because of the different structures of agricultural products. Consequently, to predict the rate of drying and optimization of drying parameters, suitable kinetic model is needed. Researchers of drying kinetics of biological materials have proposed many models. Some of the commonly used models are shown in Table 2.2.

Thin layer drying models for describing drying phenomenon of agricultural products are usually based on liquid diffusion theory which is well explained by Fick's second law (Guan *et al.*, 2013). The process of drying samples of products at uniform airflow rate, same humidity and constant temperature is called thin-layer drying (Naderinezhad *et al.*, 2016). In practice, a food dryer is considerably more multifaceted than a device that merely removes moisture. Effective models are necessary for process design, optimization, energy integration, and control. This can in turn affect the design and manufacture of various dryers especially those that require control of the process parameters.

S/No	Model name	Model	Product dried	Reference
1)	Newton	$MR = \exp(-kt)$	Pumpkin slices	Olurin *et al.* (2012)
2)	Page	$MR = \exp(-kt^n)$	Banana slices, Diced cassava roots, beef meat slices, tilapia fillets	Da Silva *et al.* (2014), Kajuna *et al.* (2001), Ahmat *et al.* (2015).
3)	Modified Page	$MR = \exp - (kt)^n$	Pumpkin slices	Olurin *et al.* (2012)
4)	Henderson and Pabis	$MR = a\exp(-kt)$	Pumpkin slices	Onwude *et al.* (2016)
5)	Logarithmic	$MR = a\exp(-kt) + c$	Apricot, wood, pumpkin	Mirzaee *et al.* (2010), Sridhar and Madhu (2015), Olurin *et al.* (2012)
6)	Simplified Fick's Diffusion Equation	$MR = a\exp - k\left(\frac{t}{L^2}\right)$	Pumpkin slices	Fernando and Amarasinghe (2016). Alibas (2012)
7)	Modified page equation11	$MR = \exp\left[-k\left(\frac{t}{L^2}\right)^n\right]$	Mint leaves Red chilli pepper cocoa	Gaol *et al.* (2015), Alibas (2012), Da Silva *et al.* (2014)
8)	Demir *et.al*	$MR = a\exp(-kt)^n + c$	Mint leaves Red chilli pepper cocoa	Gaol *et al.* (2015), Alibas (2012), Da Silva *et al.* (2014), Hii *et al.* (2009), Kajuna *et al.* (2001)
9)	Aghbashlo *et.al*	$MR = \exp\left[\frac{-k_1 t}{1 + k_2 t}\right]$	Mint leaves Red chilli pepper cocoa	Gaol *et al.* (2015), Alibas (2012), Da Silva *et al.* (2014), Hii *et al.* (2009), Kajuna *et al.* (2001), Mirzaee *et al.* (2010)

Although modelling studies in food drying is important, there is no theoretical model that is neither practical nor able to unify the calculations for the drying models. The principle of modelling is based on having a set of mathematical equations that can satisfactorily explain the system. The solution of these equations allow calculations of process parameters as a function of time at any point in the dryer based on primary condition (Garavand *et al.*, 2011). According to Ronoh *et al.* (2010), thin layer drying models mainly fall into three categories: empirical, semi-empirical and theoretical. Empirical models give a direct relationship between the average moisture content and drying time. The major limitation in applying empirical models in thin-layer drying is that they do not follow the theoretical fundamentals of drying processes in form of kinetic relationship between the rate constant and moisture concentration, thus giving inaccurate parameter values.

The empirical models do not have good physical interpretation and wholly depends on experimental data. Onwude *et al.* (2016) reported three most widely applied empirical models for drying kinetics of agricultural produce, namely: Weibull Model, Wang and Singh, Diamante and Thompson Model. Theoretical models accounts for different moisture transfer mechanisms that involve the solution of coupled or uncoupled heat and mass transfer equations. They also consider both external and internal resistance to moisture transfer. They involve the geometry of material, its mass diffusivity and conductivity of the material.

The semi-theoretical models are derived from theoretical model (Fick's second law of diffusion) or its simplified variation (Newton's law of cooling). The Lewis, Page, and Modified Page models are derived from Newton's law of cooling. The exponential model and their simplified forms like 2-term exponential model, their modified forms, 3-term exponential model, and simplified form are all derived from Fick's second law of diffusion. Some of the factors that could determine application of these models include drying temperature, drying air velocity, material thickness, initial moisture content, and relative humidity (Onwude *et al.*, 2016).

The best drying model depends on various statistics. Some of the statistical indicators often used to select the most appropriate drying models as reported in literature include coefficient of determination (R^2), chi square (x^2) and root mean square error (*RMSE)*. The higher the values of R^2 of a particular model the more appropriate the model is in predicting drying behaviour of particular products. Similarly, the lower the values of x^2 and RMSE of a particular model the more suitable the model is in predicting drying kinetics of particular products (Onwude *et al.*, 2016). The statistical indicators are expressed in equations 2.4, 2.5 and 2.6 where N and z represent the number of observations and constants respectively, while $MR_{exp,i}$ is the experimental moisture ratio and $MR_{pre,i}$ is the predicted moisture ratio.

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)\right]^2\left[\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)\right]^2}} \qquad 2.4$$

$$RMSE = \left[\frac{1}{z}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \qquad 2.5$$

$$x^2 = \frac{\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)}{N - z} \qquad 2.6$$

Even though some of the previous researchers have provided general models as a function of parameter that affect drying process of various agricultural products especially plant materials, there is limited study about the models on drying rate of egg slices.

In this study, the effects of air temperature, airflow rate, and egg slice thickness on drying rate and protein content of egg slices in an experimental forced convective dryer were experimentally investigated.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Experimental dryer and egg sample preparation

3.1.1 Drying system

Figure 3.1 shows a schematic layout of the experimental dryer used for the experimentation. It comprised of a centrifugal fan that was used to push drying air through the system. The drying system composed of two 1.8 kW electrical heaters that were used to heat the drying air. Airflow rate was varied by three different pulley sizes to produce airflow rates of 0.09 m^3/s, 0.12 m^3/s and 0.15 m^3/s respectively. The drying chamber was used to dry the various slice thickness of hardened eggs at varying drying temperatures and airflow rates. The sliced eggs were placed in perforated tray with 45% opening to allow drying air pass through the sliced eggs. The area of the chamber was 0.01 m^2 while the various pulley sizes were 110 mm diameter (smaller), 130 mm diameter (medium), and 150 mm diameter (larger). The relative humidity of the drying air was measured using hygrometer PCE-555 type and the drying relative humidity ranged from 16% to 50% depending on the actual drying conditions.

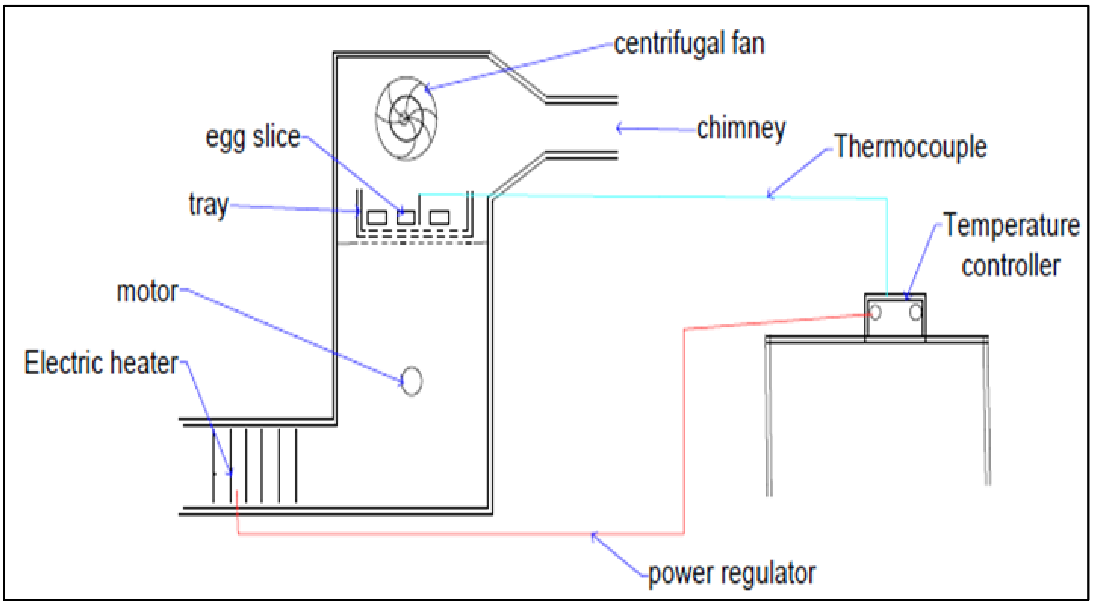

Figure 3.1: Schematic layout of the experimental forced convection dryer

The system was operated by setting the required temperature in the PID device, changing pulleys and drying different slice sizes. The slices were removed every 20 minutes by opening the top lid for weight measurement and then returned to the drying chamber then covered again with the top lid. This was repeated depending on the experiment being done.

3.1.2 Sample preparation

Grade1 (an egg without any blood spot, oval shaped and not shrunken) hen eggs were obtained from the Egerton University Tatton Farm. They were candled to confirm their freshness. The eggs were then washed using clean water and then dipped in boiling water at 90^{o}C for 17 minutes to harden them. They were removed and their average weight measured using digital weighing balance (Model: Precisa310M). Thereafter, their shells were removed and their average weight determined again. Using a sharp knife, they were sliced into 10 mm thickness. The slices were arranged into single layer leaving 45% open spaces for air to pass through and subjected to the various drying conditions of 0.09 m^3/s, 0.12 m^3/s, and 0.15 m^3/s with temperatures of 35^{o}C, 40^{o}C, and 45^{o}C. Outdoor and drying chamber relative humidity was measured and recorded during the experiment. This was repeated for the 20 mm and 30 mm slice thickness in addition to varying the various drying conditions appropriately.

3.2 Determining the influence of airflow rate, temperature and slice thickness on drying rate and protein content

3.2.1 Determining drying rate and protein content

a) Determining drying rate

The initial moisture content of eggs before experimentation was determined by the oven drying method as prescribed in the ASAE standards S352.2 on dry basis moisture content (Tang and Sokhansanj, 1991). In determining drying rate, the sliced eggs were sampled every 20 minutes from tray and weighed using the Precisa 310M digital weighing balance. The resulting data was then used to determine drying rate using equation 3.1 where dr, m_i, m_{i+1}, and Δt are drying rate, previous moisture content (dry basis), subsequent moisture content (dry basis), change in time, and i = 0,1,2,3...10 respectively.

$$dr = \left[\frac{m_i - m_{i+1}}{\Delta t} \right] \quad 3.1$$

The variation of drying rate (g/g min) for the various parameters with time were analysed and presented in section 4.1.1.

b) Determining protein content

The Kjeldahl method of nitrogen analysis was used for the protein analysis (Mauer and Bradley, 2017). The dried egg slices were ground into particles that would pass through a 20µm-mesh screen. Then, using a digital balance, 1 gram was measured out for each sample for the protein analysis purposes. The 1 gram was placed in a Kjeldahl flask. Sulphuric acid and catalyst were added; and digested until clear and a complete breakdown of all organic matter. Non-volatile ammonium sulphate was then formed from the reaction of nitrogen and sulphuric acid. During digestion, protein nitrogen was then liberated to form ammonium ions. Sulphuric acid was used to oxidize organic matter and combine with the formed ammonium; then carbon and hydrogen elements were converted to carbon dioxide and water. The digest was diluted with water and followed by sodium thiosulphate was added to neutralize the acid. The ammonia formed was distilled into a boric acid solution containing the indicators methylene blue and methyl red which is very useful in protein analysis (García *et al.*, 2013). Then borate anions were titrated with standardized hydrochloric acid.

The amount of ammonia that had been trapped was determined by titrating with a standard solution, and the percentage nitrogen (N) and crude protein (C.P) using equations (3.2) and (3.3). The protein factor used for egg was 6.25.

$$\%N = Ns \times (V1 - V2) \times f \times 0.014 \times \frac{100}{V} \times \frac{100}{S} \qquad 3.2$$

$$C.P = \%N \times P.F \qquad 3.3$$

3.2.2 Determining the influence of airflow rate on drying rate and protein content

To determine effect of airflow rate, on egg drying process, the egg slices were tested at airflow rates of 0.09 m³/s, 0.12 m³/s, and 0.15 m³/s. The control of fixed flow rate was achieved using different pulleys sizes that were designed to give the desired airflow rate over a constant cross-sectional area. Temperature was controlled using proportional integral device (PID) and then confirmed using a digital anemometer that measured the exit velocity and its temperature. The velocity was then multiplied by constant exit area to give the required airflow rate. The desired airflow rate at given temperature was directed to the drying chamber to dehydrate sliced eggs of thickness 10 mm, 20 mm, and 30 mm. The influence of varying airflow rate on drying rate and protein content were presented, analysed and discussed in section 4.1.1.

3.2.3 Determining the influence of temperature on drying rate and protein content

To determine the influence of temperature on egg drying process, experiments were done in laboratory conditions where air temperature was varied. The given samples were dried at an exit airflow rate of 0.09 m³/s and 35°C, while determining the drying rate after every 20 minutes using equation 3.1. This was repeated at 40°C and 45°C, maintaining the same slice thickness and exit airflow rate in order to observe the influence of temperature on drying rate. The procedure was repeated for 0.12 m^3/s and 0.15 m^3/s airflow rates with 20 mm and 30 mm egg slice thicknesses. The dried samples were appropriately labelled according to their drying air temperature, airflow rate and slice thickness. The samples were taken for protein analysis to investigate the influence of temperature variation on the protein content. Variation of drying rate as well as protein content with temperature variation was presented and analysed in section 4.1.2.

3.2.4 Determining the influence of slice thickness on drying rate and protein content

The temperature was fixed at 35ºC and constant airflow rate of 0.15 m^3/s was used. The slices were arranged in layers of 10 mm, 20 mm, and 30 mm vertically in the drying chamber based on the slice thickness under experimentation. The variations of thickness and its influence on drying rate and protein content were analysed and presented in section 4.1.3.

3.3 Evaluating and optimising egg drying process

Taguchi approach was used to find the optimum combination of airflow rate, temperature and egg slice thickness in terms of:

i. Maximum drying rate and
ii. Maximum protein content

The three parameters and their levels shown in Table 3.1 were used to run the experiments.

Table 3.1: Drying Process Parameters and their Levels

Factor	Parameter	units	Level 1	Level 2	Level 3
A	Airflow rate	m^3/s	0.09	0.12	0.15
B	Slice thickness	mm	10	20	30
C	Temperature	ºC	35	40	45

L_9 orthogonal array involving nine experiments was used (Table A.3 in the appendix). In each experiment, a specific slice thickness of hardened eggs slices was dried in the experimental egg dryer using electrically heated air at a specified airflow rate. The egg slices were weighed using a digital weighing balance (Precisa 310M) at the beginning, and again at the end of every drying session for 200 minutes. Drying rate and moisture ratio were determined using equation 3.1 and equation 3.4 while the S/N ratio was calculated using equation 2.3 using the larger the better criterion. The mean S/N values for each parameter level were calculated and used to determine the optimal combination of airflow rate, drying temperature and egg slice thickness for maximizing the drying rate and protein content of eggs.

$$MR = \frac{(M - M_e)}{(M_o - M_e)} \qquad 3.4$$

3.4 Testing and validating the best thin layer drying model

3.4.1 Selecting and testing thin layer drying model

Drying 30 mm egg slice thickness with fixed airflow rate of 0.15 m^3/s was chosen for the current experiment. Drying temperatures were 35ºC, 40ºC, and 45ºC; and the time to retrieved sample was every 20 minutes. This experiment was done until there was insignificant mass change in the dried eggs. Moisture content on dry basis was determined every time the sample was retrieved and their moisture ratio determined using equation 3.4. Microsoft (MS) Excel 2010 version was used to produce graph for variation of moisture ration with time. The same tool was used to determine the best fitting trend lines and regression equations for the curves. Regression equations for moisture ratio, along with selected drying models, were tested to select the best fit for the experimental data. This was achieved through determining coefficient of determination *(R^2)* (equation 2.4), RMSE (equation 2.5) and χ^2 (equation 2.6). The best model was selected based on the highest values of R^2, and lowest values of both χ^2 and RMSE.

3.4.2 Determining drying coefficients

Model coefficients constants were determined and verified for 35°C, 40°C, and 45°C then applied in simulation process. This was achieved by linearizing the approximated experimental moisture ratio data. For instance, 10 mm thick egg layer was dried until it attained constant moisture content using airflow rate 0.09 m^3/s with its moisture content determined every 20 minutes. Moisture content was converted to moisture ratio that was used to determine the variation of moisture ratio with time during drying. Drying data was customized into the MS Excel 2010, and the experimental data for variation of moisture ratio at 35°C fitted to it while using coefficient of determination (R^2), chi square (x^2) and *RMSE* to determine the best fit the experimental moisture ratio data.

The same was repeated for the subsequent temperatures of 40°C and 45°C with all drying models being tested. The constants obtained and the best model was used to simulate the drying process of hardened egg at given temperature conditions. During simulation process, input parameters were drying time and the drying constants, b, k, and n in addition to coefficient *a*. The output parameter was the predicted moisture ratio. The predicted moisture ratio was used to determine moisture content at any given time for known initial moisture content. The models obtained in sections 3.4.1 and the model constants determined in 3.4.2 were used to test the model.

3.4.3 Validating the model

The model was validated by comparing predicted moisture ratio for the nine models with the experimental moisture ratio. The coefficient of determination (R^2), root mean square error (RMSE), and chi-square (x^2) between the predicted and experimental moisture ratios were determined to test for a model with minimal deviations between predicted and experimental results in the drying process of eggs. Kituu *et al.* (2010), Mirzaee *et al.* (2010), Olurin *et al.* (2012), and Wang *et al.* (2007) reported that higher R^2 value and the lower RMSE, and x^2, gives a better goodness of the fit. The three determination parameters were evaluated using equations 2.4, 2.5, and 2.6 respectively. The results obtained were presented and discussed in section 4.3.3.

3.5 Data analysis

Data analysis was based on factorial experiments where each parameter was done in three levels. The Microsoft 2010 version was used to analyse the data on the influence of varying the parameters on drying rate and protein content of hardened eggs. Taguchi technique used was the larger the better criterion and customized into Microsoft 2010 excel for analysis. Analysis of variance (ANOVA), regression and graphical representation were used to analyse data for the influence of varying airflow rate, temperature and slice thickness on drying rate and protein content of dried eggs. To scrutinize whether there was a significant difference in their means, least significant difference (LSD) was performed at 5% significance level. The ANOVA and some graphical representation results were given in the appendices.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

In this chapter, the results obtained from the experiments are presented and discussed. Raw data used to obtain Tables and Figures presented in this section are attached in appendix 1 and appendix 2. The relative humidity inside the drying chamber during experimentation ranged from 16% to 50% as shown in Table A.1 in the appendix. The ambient relative humidity outside the drying chamber ranged from 61% to 90%. The high variation in the Relative humidity was due high variation in the weather conditions during experimentation period.

4.1 Influence of airflow rate, temperature and slice thickness on drying rate and protein content

Results for the effects of varying airflow rates, temperatures, and layers on drying rate and protein content of eggs are presented and discussed in the following subsections 4.1.1 to 4.1.6.

4.1.1 Influence of airflow rate on drying rate

The drying rate for the three airflow rates increased from 0.68 to 0.76 g/g min at fixed slice thickness of 10 mm. Drying rate also increased from 0.67 to 0.76 g/g min at fixed temperature of 45^oC (Table 4.1). Thus, drying rate increased with increase in drying airflow rate.

This observation agreed with Ficks' law in which high airflow rate caused high concentration gradient between the drying air and product interface. High concentration gradient resulted in high moisture transfer from the egg slices hence increasing drying rate. This agreed with Jekayinfa (2006) results indicating that increasing air flow rates results to increased diffusion gradient during drying. The high diffusion gradient caused high drying rate of eggs with rise in airflow rate.

Variation of airflow rate had significant effect ($p<0.05$) on the drying rate of eggs at both fixed thickness and temperature as shown in Tables 4.1. This variation was more at high airflow rate of 0.15 m^3/s as compared to lower airflow rate (0.09 m^3/s and 0.12 m^3/s) that were insignificant.

Table 4.1: Drying rate for various airflow rates at constant temperature and thickness

Airflow rate (m³/s)	Drying rate (g/g min)	
	Temperature (45ºC)	**Thickness (10 mm)**
0.09	0.68[a]	0.67[a]
0.12	0.69[a]	0.68[a]
0.15	0.76[b]	0.76[b]
	LSD=0.03	**LSD=0.04**

An average value followed by the same letter(s) (a, b, c) in same column are not significantly different at α=5% level of significant using LSD.

Drying rate increased with increase in airflow rates as shown in figure 4.1. The drying curve exhibited an exponential trend. However, after 120 minutes, the difference in the drying rate among the three airflow rates decrease. This shows that the influence of airflow rate on drying rate as the product being dried approached equilibrium moisture content was insignificant (Table A.8 in the Appendix). Thus, the product started approaching equilibrium moisture content after 120 minutes of drying. This was because when equilibrium moisture content is approached, drying rate reduces. This explains the convergence of the drying curve.

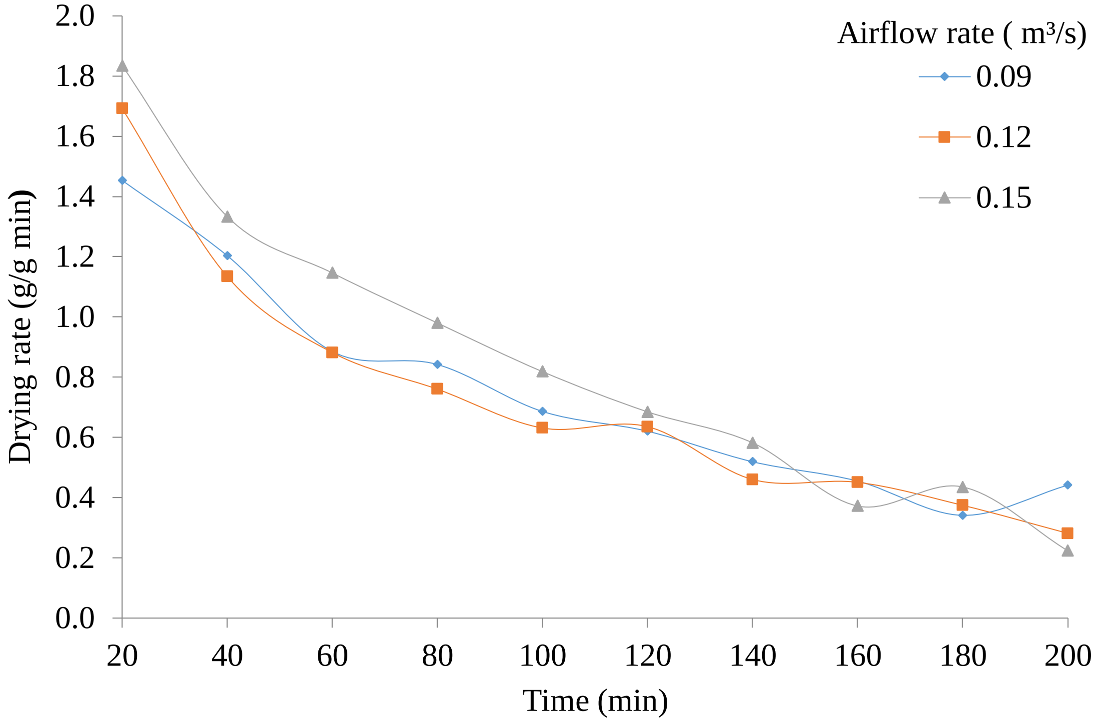

Figure 4.1: Drying curves for varying airflow rates at 45ºC and 10 mm thickness

Figure 4.2 shows the trend as airflow rate increased at various fixed temperatures on drying rate. It was deduced that regardless of the temperature, drying rate increased as airflow rate increased and vice-versa. This compares well with Putra and Ajiwiguna (2017), Panchariya *et al.* (2002) and Velić *et al.* (2004) in drying process of black tea and apple. Velić *et al.* (2004) found that increasing airflow rate raised drying rates of apple. Their findings also indicate that an increase in airflow rate reduced time required to dry agricultural products.

Similarly, Figure 4.3 shows that drying rate increased as the airflow rate under various fixed slice thicknesses. From Figures 4.2 and 4.3, it was observed that the influence of airflow rate diminished as both the temperatures decreased and thickness increased.

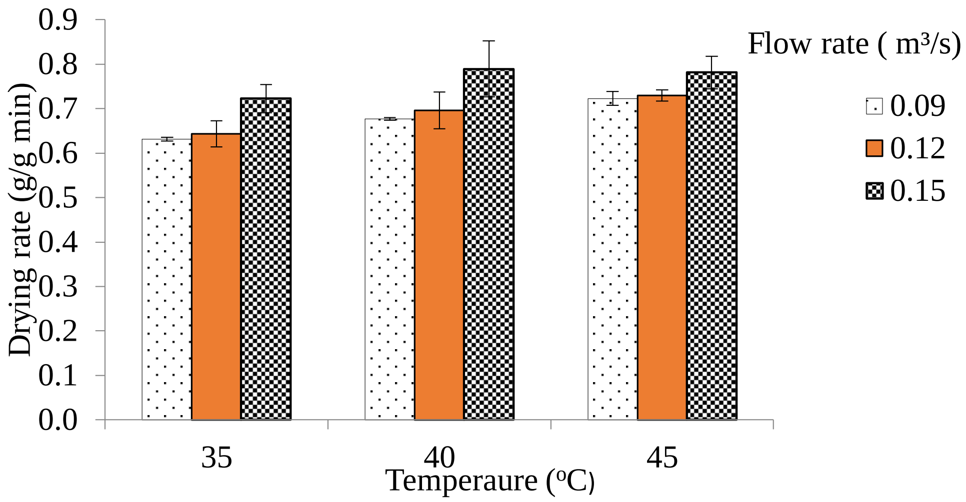

Figure 4.2: Effects of temperature and flow rates on drying rate at 10 mm

Similarly, Figure 4.3 show that drying rate increased as the airflow rate under various fixed slice thicknesses. The influence of airflow rate on drying rate was diminishing as temperature decreased and thickness increased.

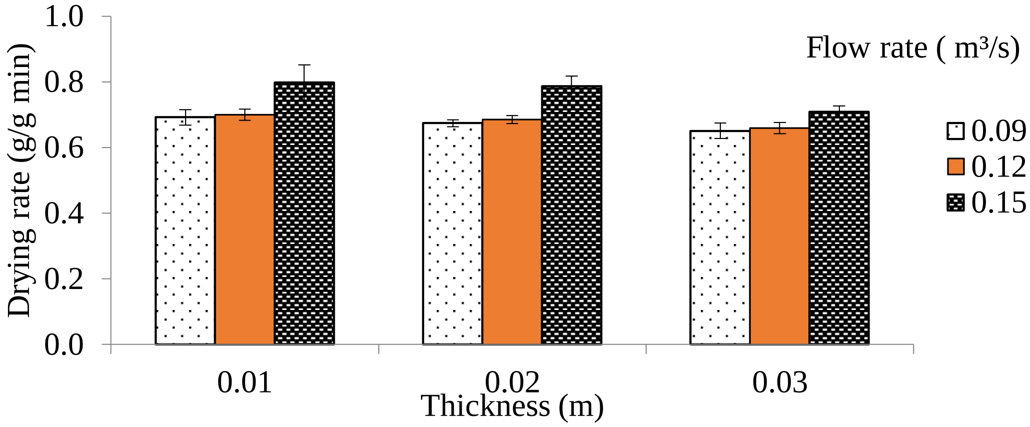

Figure 4.3: Drying rate at different thicknesses and flow rates at 45°C

The different sizes of error bars in both Figure 4.2 and Figure 4.3 indicates a significant difference in the mean drying rates due the influence of airflow rate.

4.1.2 Influence of temperature on drying rate

Table 4.2 shows that drying rate increased from 0.67 to 0.75 g/g min at constant airflow rate of 0.15 m^3/s with increase in temperature from 35°C to 45°C. The drying rate also increased from 0.62 to 0.72 g/g min at constant thickness of 10 mm as temperature increased from 35°C to 45°C. This shows that lower temperature has lower drying rate and increased as temperature rises. Accordingly, high temperature increased temperature gradient resulting to more heat transfer to the product. As a result, water molecules were energised leading to high rate of diffusion. This led to high drying rate as temperature increased. Therefore, it took shorter time to dry egg slices at higher temperature and longer time when drying at lower temperature.

Table 4.2: Drying rates for temperatures at constant airflow rate and thickness

	Drying rate (g/g min)	
Temperature (°C)	**Airflow rate (0.15 m^3/s)**	**Thickness (10 mm)**
35	0.67^a	0.62^a
40	0.71^b	0.70^b
45	0.75^c	0.72^c
	LSD=0.03	**LSD=0.02**

An average value followed by the same letter(s) (a, b, c) in same column are not significantly different at α=5% level of significant using LSD.

It is also found that temperature had significant effect ($p<0.05$) on drying rate of eggs under fixed airflow rate and slice thickness. Drying rate of egg slices increased as temperature rose from 35°C to 45°C. This observation compared well with the works of Guan *et al.* (2013), and Kituu *et al.* (2010) in tilapia fillet drying and other agricultural products.

Figure 4.4 shows the different exponential drying curves of eggs at three temperatures being investigated from which drying rate increased as temperature increased. However, from 100 minutes to 200 minutes, drying curves started merging due to decreased deviations among them. Therefore, as equilibrium moisture content of the egg slices approached, the influence of temperature became insignificant ($p>0.05$). This is shown in Table A.9 in the appendix where a single factor ANOVA was done for the last 100 minutes of drying. This was because the drying eggs were approaching their equilibrium moisture content at the given conditions. The mix up of the three curves was due to different drying rates of egg york and the egg white.

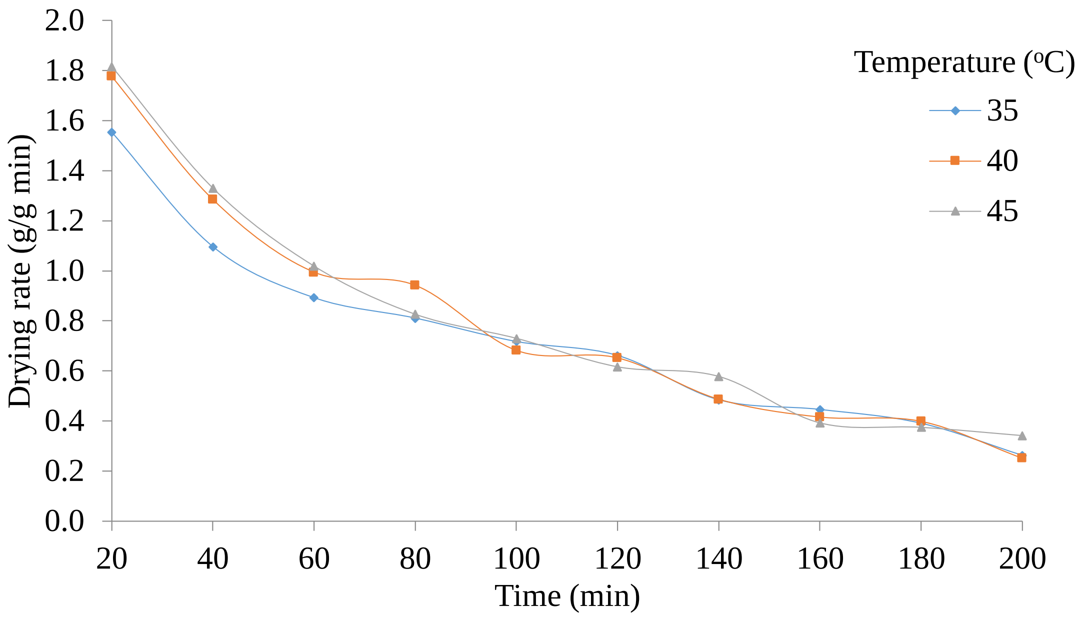

Figure 4.4: Drying curves for varying temperature at 0.15 m³/s and 10 mm thickness

Figure 4.5 shows the effect of temperature under varying airflow rate on drying rate. The drying rate increased with increase in temperature at constant airflow rate. This compared well with Limpaiboon (2011) and Putra and Ajiwiguna (2017) who reported that an increase in drying temperature increased drying rate. The drying rate was initially high but decreased at higher temperatures because it needed more energy for moisture transfer.

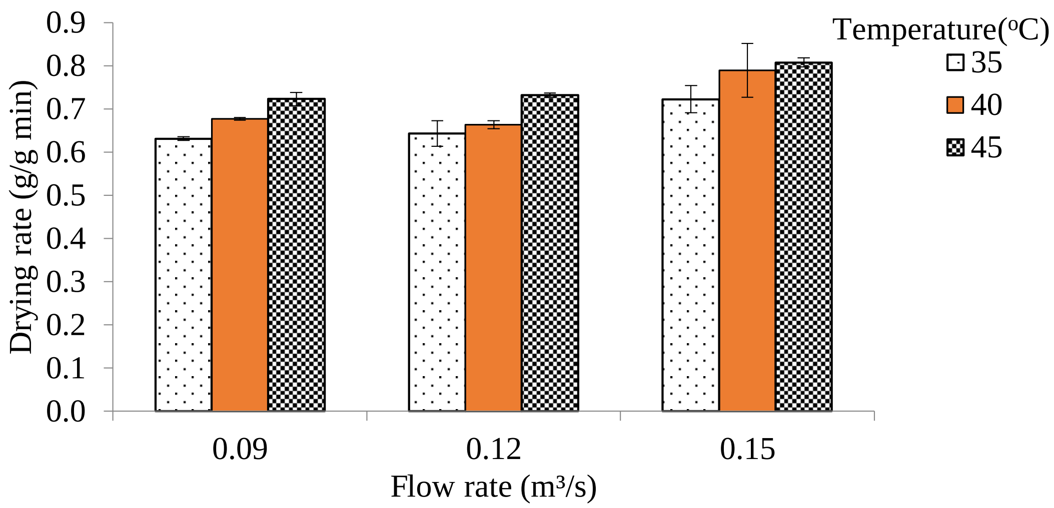

Figure 4.5: Airflow rate and temperature influence on drying rate

The same trend was also true at the three levels of thicknesses as shown in Figure 4.6.

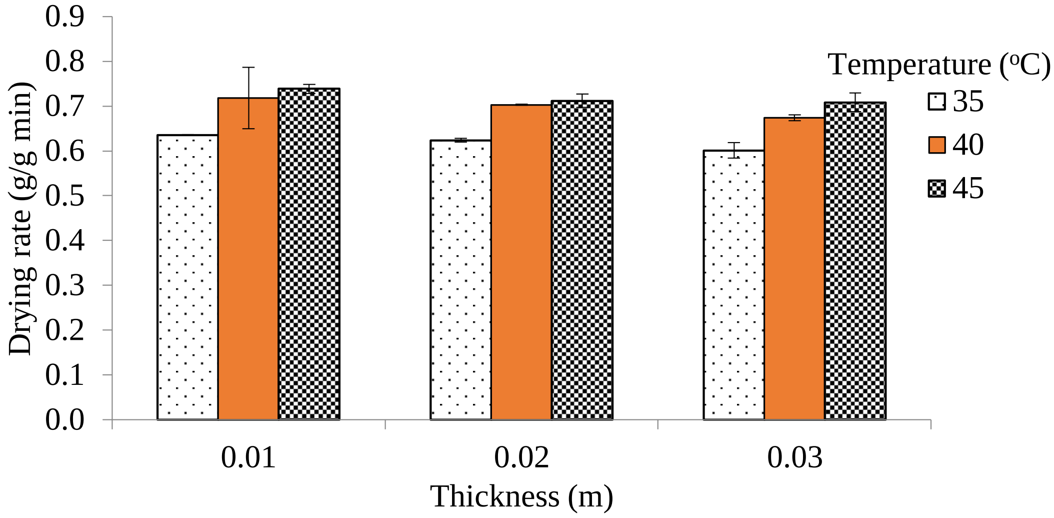

Figure 4.6: Slice thicknesses and temperature influence on drying rate

The different error bar sizes in both Figure 4.5 and Figure 4.6 indicate the that there was significant difference in the mean drying rate due to the influence of temperature increment.

4.1.3 Influence of slice thickness on drying rate

Drying rate decreased from 0.72 to 0.68 g/g min with increase in thickness from 10 mm to 30 mm at fixed temperature of 45°C (Table 4.3). The drying rate also decreased from 0.71 to 0.67 g/g min at constant airflow rate of 0.15 m^3/s as shown in Table 4.3. Thus, increasing slice thickness reduced drying rate of eggs. This agreed with Fick's and Fouriers' law in which increase in thickness lowered heat and mass transfer resulting to low drying rate. For instance, with Ficks' law, an increase in thickness over which diffusion of moisture occur causes low mass flow hence low drying rate. Conversely, a decrease in thickness caused high heat and mass transfer to and from the product leading to high drying rate.

Table 4.3: Drying rate for varying thickness at constant temperature and airflow rate

	Drying rate (g/g min)	
Slice thickness (mm)	**Temperature (45°C)**	**Airflow rate (0.15 m^3/s)**
10	0.72^a	0.71^a
20	0.69^b	0.70^a
30	0.68^c	0.67^a
	LSD=0.01	**LSD=0.05**

An average value followed by the same letter(s) (a, b, c) in same column are not significantly different at α=5% level of significant using LSD.

Thickness variation at constant temperatures has significant effect ($p<0.05$) and insignificant effect ($p>0.05$) on drying rate with fixed airflow rates. This compared well with Diamante (1994), Kabiru *et al.* (2013), Kajuna *et al.* (2001) and Limpaiboon (2011) in diced cassava roots, tomato slices, pumpkin slices, mushroom and mango slices where thickness variation affects drying rate of agricultural products.

Figure 4.7 showed different exponential drying curves of eggs at three thicknesses under investigation. The drying rate decreased as thickness increased. The drying rate was high in the first 60 minutes but decreased rapidly as time progressed. After 140 minutes, the started approaching equilibrium moisture content hence the influence of slice thickness was insignificant ($p>0.05$). This can be seen from the single factor ANOVA (Table A.10 in the appendix). This also reduced diffusion gradient, hence reduced drying rate. Consequently, high thickness resulted to reduce mass flow rate and heat transfer. This compared well with other researchers (Kabiru *et al.*, 2013; Limpaiboon, 2011; Stegou and Fragkou, 2015) who observed same trend in drying pumpkin, mango and mushroom slices.

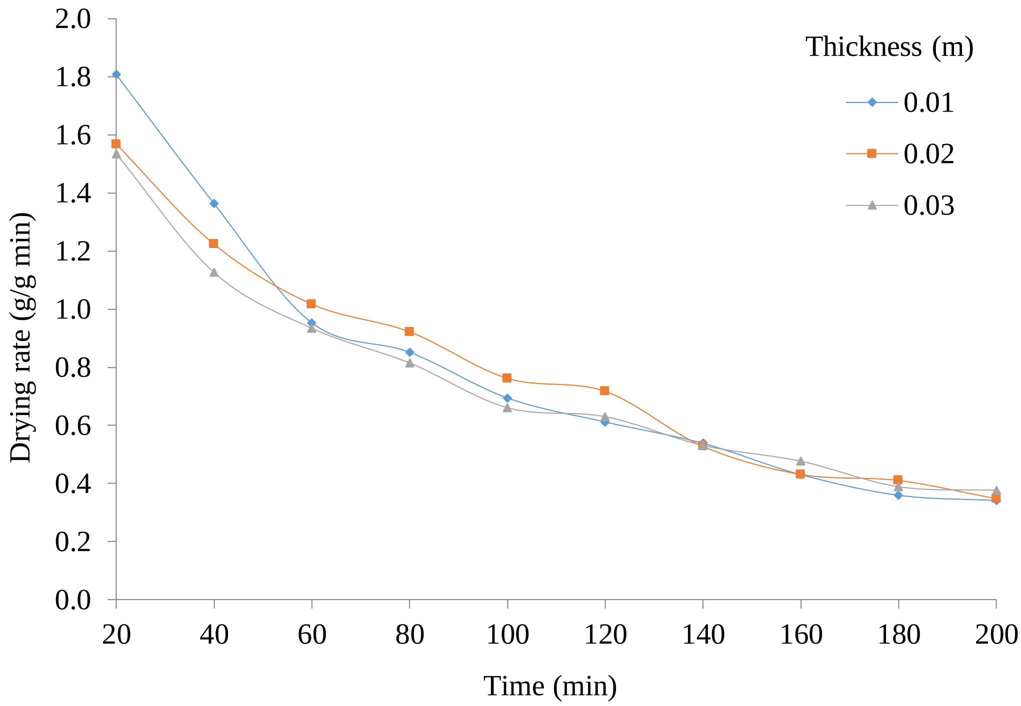

Figure 4.7: Drying curve for varying thicknesses at 45°C and airflow rate of 0.15 m³/s

Figure 4.8 shows the overall effects of varying thickness at various temperatures on drying rate. The drying rate was higher in 10 mm slice thickness and decreased as the slice thickness increased at fixed temperatures.

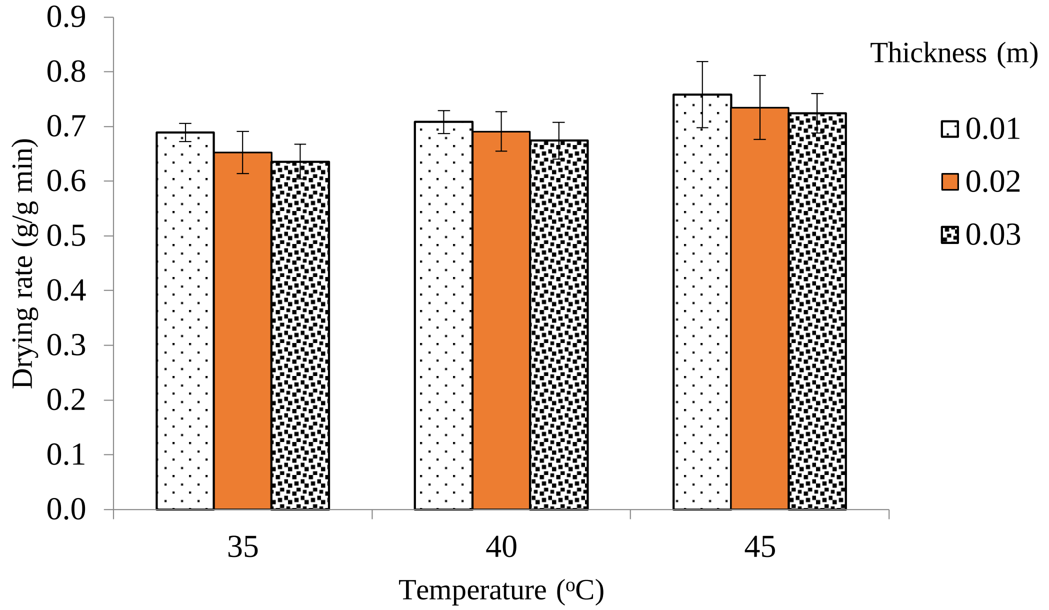

Figure 4.8: Drying rate at different thicknesses and temperature

Drying rate also decreased with increase in slice thickness under various fixed airflow rates as shown in Figure 4.9. This compared well with Sadin *et al.* (2014) who reported that shorter time is taken to dry smaller thickness over the larger thickness. This was because the smaller thickness increased diffusion process from the inner core to the outer core hence high drying rate.

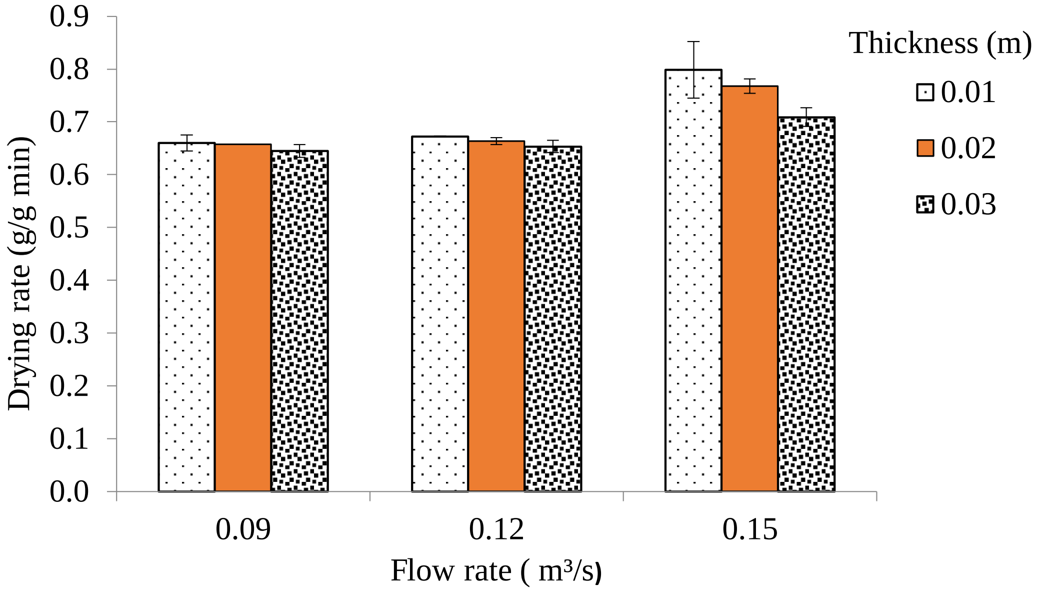

Figure 4.9: Drying rate at different thicknesses and airflow rates

The different sizes of error bars from Figure 4.8 and Figure 4.9 shows a significant different in the mean drying rates due variation in slice thickness of the boiled eggs.

4.1.4 Influence of airflow rate on protein content

Table 4.4 shows the influence of flow rate on dried eggs' protein content from which mean protein content decreased from 54.4% to 48.3% with increase in airflow rate from 0.09 m^3/s to 0.15 m^3/s. This was at fixed egg slice thickness of 10 mm. This was because as airflow rate increased, heat transfer that denatures protein content increased leading to low protein content. High mass transfer leads to increased removal of moisture hence percentage of protein content in dry basis increases especially at temperatures that do not denature the proteins. This agreed with Omodara and Olaniyan (2012) where protein content decreased with increase in heat transfer during drying of cat fish.

Table 4.4: Protein content with varying airflow rate and temperature at fixed thickness

	Flow rate			
Temperature (^oC)	**0.09 m^3/s**	**0.12 m^3/s**	**0.15 m^3/s**	**Mean (LSD=3.2)**
35	56.0*	55.7	52.0	**54.6^a**
40	55.7	51.3	47.9	**51.6^a**
45	51.4	46.4	44.8	**47.5^b**
Mean (LSD=3.2)	**54.4^x**	**51.1^y**	**48.3^y**	

** % Protein content*

An average value followed by the same letter(s) (a, b, c) in same column; (x, y, z) in same row are not significantly different at α=5% level of significant using LSD.

Figure 4.10 shows variation of protein content with airflow rate and temperature at thickness of 20 mm. It shows that protein content decreased with increase in temperature and airflow rate. Again, boiling of eggs slightly lowered protein content as observed from Figure 4.10.

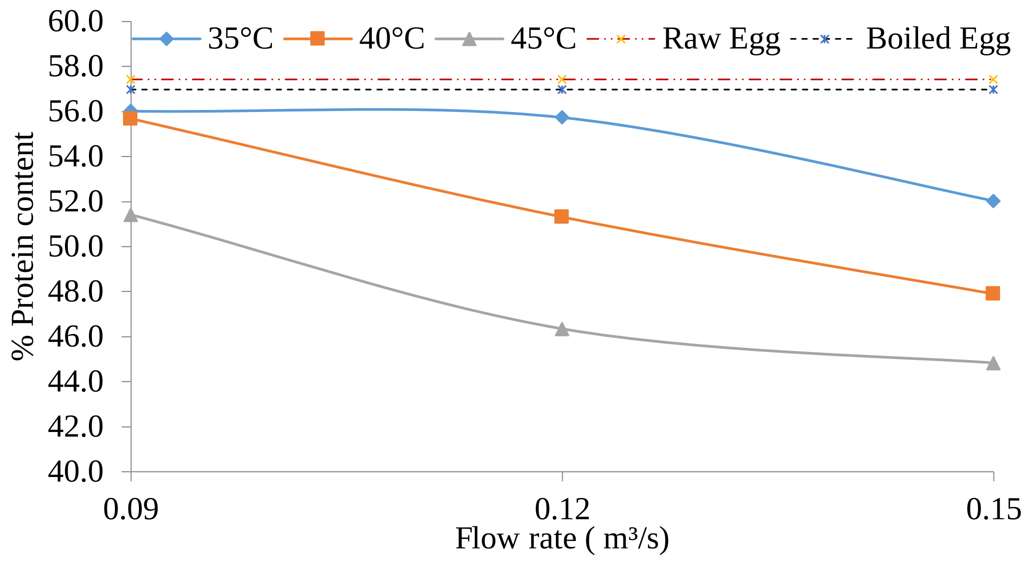

Figure 4.10: Protein variations with airflow rate and temperature at 30 mm thickness

Table A.5 in the appendix shows a two-way analysis of variance without replication for flow rate and temperature. The airflow rate had significant influence on the protein content of dried eggs (p<0.05). Thiagarajan (2008) found similar trends from which airflow rate influenced chemical components with protein included in dried beef jerky.

4.1.5 Influence of Temperature on protein content

The mean protein content decreased from 53.3% to 44.5% as temperature increased as shown in Table 4.5. This was done at fixed airflow rate of 0.15 m^3/s. High heat transfer caused by increase in temperature resulted to low protein content in dried eggs. Therefore, temperature increment decreased protein content of drying eggs especially at higher temperatures. This shows that temperature variation had significant influence on the protein content of dried eggs (Table 4.5).

Table 4.5: Protein content with varying temperature and thickness at fixed airflow rate

	Thickness			
Temperature (°C)	**10 mm**	**20 mm**	**30 mm**	**Mean (LSD=8.3)**
35	48.3*	53.3	58.3	**53.3^a**
40	46.6	52.3	56.0	**51.6^a**
45	40.8	42.8	50.0	**44.5^b**
Mean (LSD=8.3)	**45.2^x**	**49.5^x**	**54.8^y**	

** % Protein content*

An average value followed by the same letter(s) (a, b, c) in same column; (x, y, z) in same row are not significantly different at α=5% level of significant using LSD.

Figure 4.11 shows variation in protein content with temperature at 0.15 m^3/s airflow rate. The protein content increased with decrease in temperature (Figure 4.11).

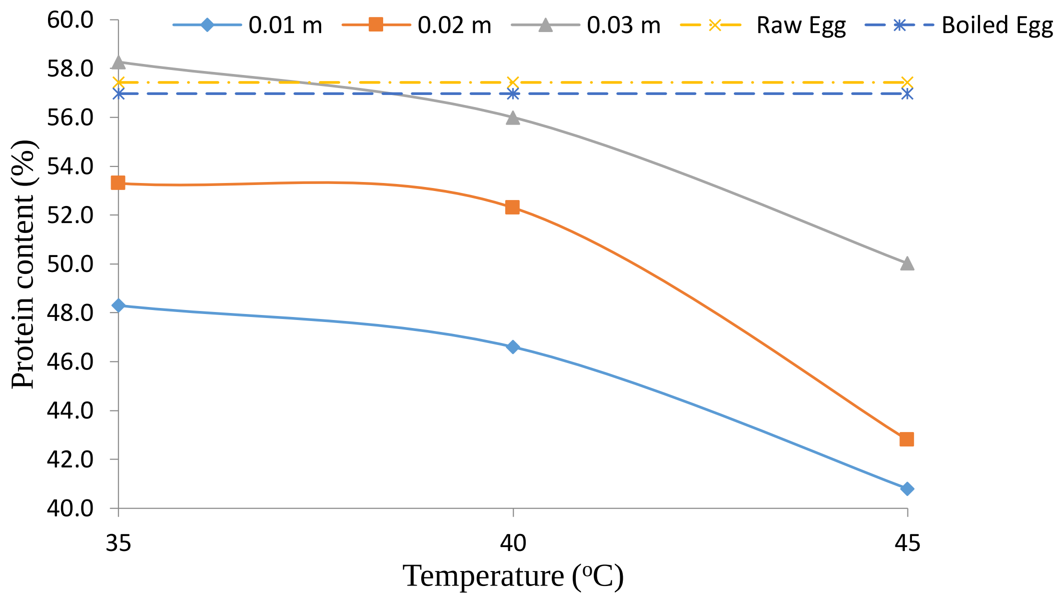

Figure 4.11: Protein variations with thickness and temperature at constant airflow rate

Thus, increase in temperature has high heat transfer that negatively affects protein content of eggs. Protein content at 35ºC and 0.03 m increased beyond the raw and boiled eggs. This could be due to more reduction in moisture content that made protein content concentration increase in terms of dry mass basis. In addition, at this condition, the protein was not being denatured due to low temperature. Thus, when eggs are dried at temperatures that do not destroy their protein content, their protein concentration increases hence the increased protein content. The increased protein content is advantageous to malnutrition problems in people.

4.1.6 Influence of slice thickness on protein content

The protein content increased from 47.9% to 53.8% as slice thickness increased from 10 mm to 30 mm as presented in Table 4.6. This was because lower thickness had high heat transfer rate as compared to high thickness. The high heat transfer in the lower thickness resulted to denaturing of protein content in eggs as compared to the larger thickness. This results to high protein content with increase in thickness. As the slice thickness increases and drying takes place at optimal levels, the concentration of protein content rises.

Zamora and Aponte (2013) reported similar trend in drying of pawpaw puree in which the influence of thickness on protein content had lower value for the samples at lower thickness.

This result was because thinner samples reached higher internal temperatures that caused further degradation of the papaya proteins.

Table 4.6: Protein content with varying thickness and airflow rate at fixed temperature

	Airflow rate			
Slice thickness (mm)	**0.09 m³/s**	**0.12 m³/s**	**0.15 m³/s**	**Mean (LSD=6.9)**
10	52.2*	48.3	43.3	**47.9[a]**
20	54.4	52.8	46.6	**51.3[a]**
30	56.6	54.8	50.1	**53.8[a]**
Mean (LSD=6.9)	**54.4[x]**	**52.0[x]**	**46.7[y]**	

** % Protein content*

An average value followed by the same letter(s) (a, b, c) in same column; (x, y, z) in same row are not significantly different at α=5% level of significant using LSD.

Figure 4.12 presents protein content with thickness at constant temperature of 35°C.

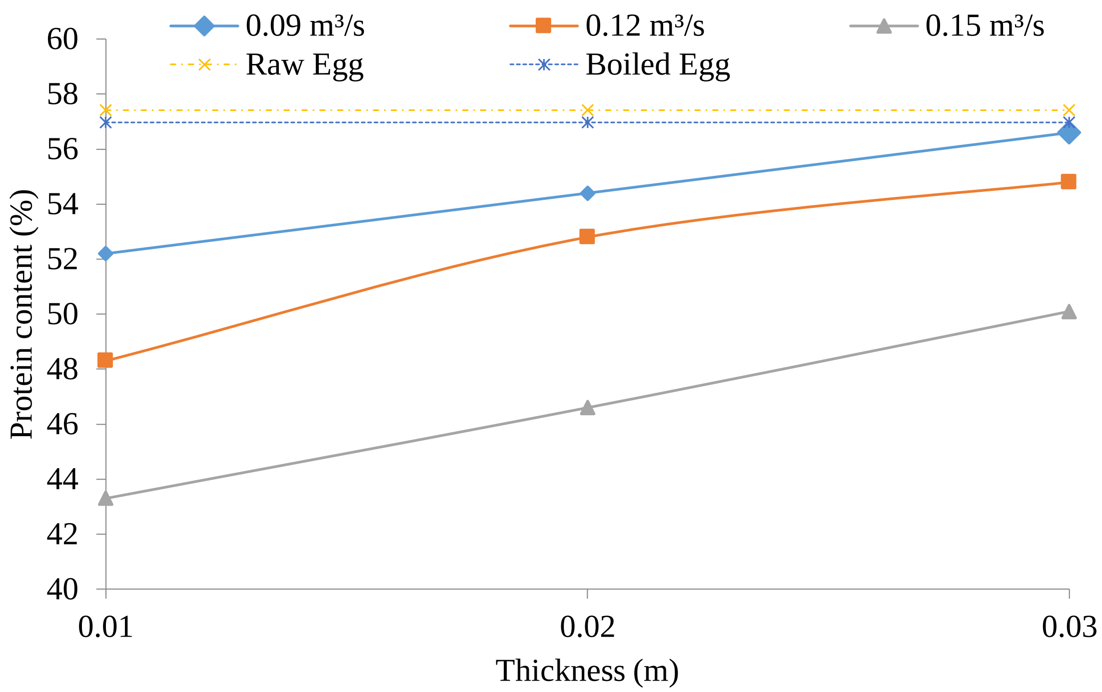

Figure 4.12: Protein variations with slice thickness and airflow rate at 35°C

Figure 4.12 shows that lower thickness had lower protein content and vice-versa. This shows that increasing slice thickness had minimal effect on protein content. This observation show that high heat transfer in lower thickness caused loss of protein content as compared to larger thicknesses due to less heat transfer process. Consequently, high protein content in eggs could be obtained by drying at 30 mm slice thickness with minimal effect on protein content of the boiled eggs.

4.2 Evaluation and optimization of egg drying process

4.2.1 Optimal drying rate conditions determination

The average drying rate at various parameters is shown in Table 4.7. The results showed that drying rate ranged from 0.61 g/g min to 0.84 g/g min. Table 4.7 further shows that the highest drying rate was obtained by the combination of 0.15 m^3/s airflow rate, 45^oC temperature and 10 mm thickness that was within the test range.

Table 4.7: Mean drying rate per Experiment

Experiment number	Airflow rate (m^3/s)	Temperature (^oC)	Thickness (mm)	Mean drying rate (g/g min)
1	0.09	35	30	0.63
2	0.09	40	10	0.68
3	0.09	45	10	0.71
4	0.12	35	20	0.67
5	0.12	40	30	0.65
6	0.12	45	10	0.67
7	0.15	35	20	0.75
8	0.15	40	30	0.73
9	0.15	45	10	0.84
10	0.09	35	10	0.64
11	0.09	40	20	0.67
12	0.09	45	30	0.74
13	0.12	35	30	0.61
14	0.12	40	10	0.67
15	0.12	45	20	0.70
16	0.15	35	30	0.73
17	0.15	40	10	0.80
18	0.15	45	10	0.75

This is further demonstrated in Table B.2 in the appendix that shows parameters and their respective S/N ratios. The maximum signal to noise ratio was achieved at for airflow rate of 0.15 m^3/s, temperature of 45^oC and 10 mm slice thickness.

Figures A.1 (see appendix) presents S/N ratio for the respective parameters. It shows that S/N ratio was high at 0.15 m^3/s airflow rate, 45^oC for temperature, and 10 mm for slice thickness. Therefore, since factor levels corresponding to the highest S/N ratio were chosen to optimize the conditions, then the optimum values of the factors and their levels were airflow rate of 0.15 m³/s, temperature of 45°C and 10 mm thickness for the current study. The optimised condition gave a drying rate of 0.84 g/g min that was highest as observed from Table 4.7.

4.2.2 Determination of most influential hardened egg drying rate parameter

The response magnitude in percentage of each parameter in the orthogonal array experiment was evaluated and results presented in Table 4.8. This was done using ANOVA to identify and quantify the most influential parameter from different runs in egg drying rate. Airflow rate had the highest influence (51%) then temperature (36%) and lastly slice thickness (9%). Therefore, the effect of slice thickness in hardened egg drying rate was low as compared to airflow rate and temperature variation. This implied that the three parameters had reasonable influence on drying process of eggs. The noise factors contributed 4% in the drying rate of eggs. This means that the noise factors like egg shrinkage and heat damage had least influence on the drying rate of eggs.

Table 4.8: Percentage sums of squares for the drying process parameters

Parameter	DOF	SS	SS (%)
Flow rate	2	0.0672	50.76
Temperature	2	0.0478	36.10
Thickness	2	0.0125	9.44
Noise (error)	2	0.0049	3.71
Total	**8**	**0.1323**	**100.00**

Athreya and Venkatesh (2012) reported that the total sums of the squares for total variation is equal to the sum squares of deviations of all parameters and their error components. This principle was used to find most influential parameter in the drying process. This demonstrated that increase in airflow rate increased the capacity to hold more moisture hence raised drying rate.

4.2.3 Optimising protein content drying parameters for hardened eggs

The average protein content at various parameters is shown in Table 4.9. The results show that protein content ranged from 41% to 57%. Table 4.9 also shows that the highest protein content was given by the combination of airflow rate of 0.15 m³/s, temperature of 35°C and 30 mm thickness.

Table 4.9: Mean protein content per Experiment

Experiment number	**Airflow rate (m^3/s)**	**Temperature (^oC)**	**Thickness (mm)**	**Protein content (%)**
1	0.09	35	30	56.17
2	0.09	40	10	54.30
3	0.09	45	10	50.67
4	0.12	35	20	40.77
5	0.12	40	30	54.57
6	0.12	45	10	43.77
7	0.15	35	20	54.93
8	0.15	40	30	55.27
9	0.15	45	10	47.20
10	0.09	35	10	53.30
11	0.09	40	20	48.33
12	0.09	45	30	42.03
13	0.12	35	30	55.03
14	0.12	40	10	49.50
15	0.12	45	20	45.90
16	0.15	35	30	57.10
17	0.15	40	10	53.51
18	0.15	45	10	53.43

Table B.3 (see appendix) shows average signal to noise ratio for each of the parameters and their respective levels. The maximum signal ratio for airflow rate was 0.15 m^3/s, temperature of 35^oC, and slice thickness of 30 mm for the hardened egg slices. This was further observed in Figures A.2 (see appendix) showing S/N ratio against the respective parameters. Therefore, the factor levels corresponding to highest S/N ratio were chosen to give maximum protein content. These conditions are maximum airflow rate, minimum temperature and maximum slice thickness. The same combination gives the highest protein content of 57.1% in the current research.

Table 4.10 shows percentage contribution of process parameters in influencing protein content. Temperature had the highest influence on protein content (41%) then airflow rate with 27% and lastly thickness with 26%. The noise contributed 6% implying least contribution in influencing protein content of dried eggs.

Table 4.10: Percentage sums of squares for protein content in dried eggs

Parameter	DOF	SS	SS (%)
Flow rate	2	227.41	26.54
Temperature	2	351.89	41.07
Thickness	2	222.99	26.03
Noise (error)	2	54.47	6.36
Total	**8**	**856.76**	**100**

Therefore, the effect of slice thickness in hardened egg protein content after drying was low as compared to airflow rate and temperature variation.

4.2.4 Optimising egg drying process

Table 4.11 presented summarised optimal conditions for hardened egg drying process. Protein content had the highest percentage change than drying rate. Thus, to maximize protein content, combination of airflow rate of 0.15 m³/s with a slice thickness of 30 mm and a temperature of 35^{o}C was appropriate in this present work. This is because increase in drying rate due to rise in temperature resulted in the lowest protein content in the dried eggs. This was obtained by identifying the optimised output (drying rate or protein content) that had the highest percentage change.

Table 4.11: Optimized conditions for hardened egg drying process

Desired output	Flow rate (m³/s)	Temperature (^{o}C)	Thickness (mm)	Drying rate (g/g min)	Protein content (%)
Drying rate	0.15	45	10	0.84	47.20
Protein content	0.15	35	30	0.73	57.10
% Change				**13.81**	**20.97**

Since protein content gave the highest change, then the optimised conditions for egg drying are airflow rate of 0.15 m³/s, temperature of 35^{o}C and 30 mm slice thickness. This combination gave protein content of 57.10% the present research (Table 4.11).

4.3 Testing and validation of thin layer drying models

4.3.1 Drying kinetics of egg slices

The drying kinetics of hardened eggs dried under a forced convection system is shown in Figure 4.13. Initial moisture content of hardened egg before drying was 227% (db). The drying temperature had significant effect on drying kinetics of hardened eggs at constant airflow rate and slice thickness. Moisture content decreased continuously with time and as temperature increased, it resulted in reduced drying time. For instance, to reduce moisture content from 227 % (db) to 24 % (db); 35^{o}C, 40^{o}C and 45^{o}C temperature took 620, 480 and 360 minutes respectively.

The reduction in moisture content at varying temperature over given time was due to two factors. This included residual heat inside the hardened egg slices that was sufficient to evaporate moisture from intermolecular spaces within the egg. Secondly, was the moisture gradient that existed between intermolecular spaces and air-product interface. The drying rate was higher at the initial stage since there was high moisture content that created high moisture gradient. This resulted to more driving force that drove moisture from inside the product to outer surface from where it was transported by flowing air. Gupta *et al.* (2002) reported similar observation in drying characteristics of red chilli where moisture diffusivity was higher at higher moisture content as compared to those at lower moisture content.

Therefore, high temperature gradient at the interface of drying egg slice caused more heat transfer to the intermolecular spaces energising moisture molecules causing mass transfer to surface. This moisture was removed from the surface by drying air leading to dehydration of the product.

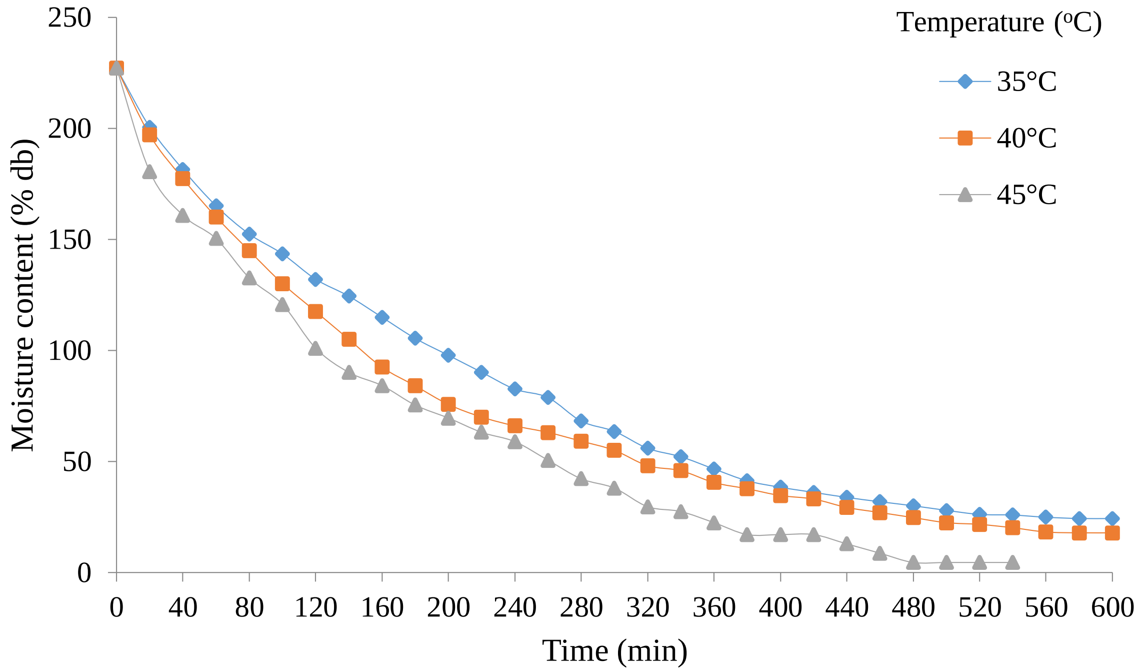

Figure 4.13: Moisture content curves at 0.15 m³/s and 30 mm thickness

The moisture content decreased with time for each of the three drying temperatures as presented in Figure. 4.13. However, as previously mentioned, drying rate was high for the first 20 minutes and thereafter the moisture content started stabilising at 200 % moisture content. This corresponded to 1.56, 1.78 and 1.82 g/g min drying rate for 35, 40 and 45°C drying air temperature respectively. This conquered well with conclusions that the rate of diffusion is proportional to the sample temperature variation as reported by Diamante (1994) and Simal *et al.* (1994). This was well observed after 360 minutes as seen in Figure 4.13.

4.3.2 Appropriate thin layer model for drying eggs

The experimental moisture ratio data observed in hardened egg drying process under different conditions were fitted to nine commonly used thin-layer drying models as shown in Table 2.2 (section 2.4) and their results shown in Table 4.14. The appropriate model describing thin layer-drying characteristic of hardened eggs was selected based on the model with highest R^2 values, lowest x^2 and RMSE values. In all cases, the R^2, x^2 and RMSE values range from 0.6141 to 0.9990, 0.0001 to 0.5429 and 0.0012 to 0.5708 respectively. Page, Modified Page and Aghbashlo et.al would predict drying kinetics of hardened eggs. However, Page model presented the highest R^2 values (0.9991), the lowest x^2 (0.0001) and RMSE (0.0012) in all three drying temperatures. Hence, Page became gave the best prediction over other models tested.

Table 4.12: Statistics for thin layer drying models of eggs at varying temperatures

Model number	Model name	Temperature (°C)	Coefficients and constants	R^2	χ^2	RMSE
1	Newton	35	k= 0.0036	0.9794	0.0159	0.1239
		40	k= 0.0045	0.9985	0.0003	0.0172
		45	k= 0.0074	0.9856	0.0038	0.0641
2	Page	35	k= 0.03154, n= 0.6716	**0.9991**	**0.0001**	**0.0012**
		40	k= 0.00644, n= 0.9351	0.9985	0.0004	0.0183
		45	k= 4.56E-03, n= 1.0578	0.9975	0.0005	0.0221
3	Modified Page	35	k= 0.00582, n= 0.6716	**0.9991**	**0.0001**	0.0116
		40	k= 0.00454, n= 0.9351	0.9985	0.0004	0.0183
		45	k= 6.13E-03, n= 1.0578	0.9975	0.0005	0.0221
4	Henderson and Pabis	35	a= 10.707867, k =0.0034	0.6141	0.0985	0.0638
		40	a= 1.0085, k =0.0045	0.9985	0.0003	0.0177
		45	a= 1.2687, k =0.0074	0.9856	0.0071	0.0809
5	Logarithmic	35	a= 0.1979, k= 0.0019, c= 0.6299	0.6311	0.2609	0.4855
		40	a= 0.16051, k= 0.003, c= 0.7748	0.6912	0.3377	0.5513
		45	a= 0.1419 k= 0.0038, c= 0.7476	0.5836	0.3666	0.5708

6	Simplified Fick's Diffusion Equation	35	a= 0.70787, k= 3E-06	0.9735	0.0045	0.0646
		40	a= 1.00874, k= 4.05E-06	0.9985	0.0003	0.0178
		45	a= 1.2687, k= 7.0 E-06	0.9794	0.0071	0.0813
7	Modified Page equation*11*	35	k= 5.24E-06,n= 0.6716	0.6705	0.5429	0.7127
		40	k= 9.44E-08,n= 1.2993	0.9913	0.0026	0.0495
		45	k= 7.40 E-09,n= 1.3477	0.9937	0.0018	0.0407
8	Aghbashlo *et al.*	35	k1= 7.14E-3, k2= 1.42E-3	0.9963	0.0009	0.0295
		40	k1= 0.00398, k2= -0.000279	0.9990	0.0004	0.0182
		45	k1= 0.00459, k2= -0.00082	0.9990	0.0005	0.0209
9	Demir *et al.*	35	a= 0.16094, c= 0.83906, k= 2.46E-3, n= 0.8091	0.6928	0.4897	0.6531
		40	a= 0.1704, c= 0.7748, k= 0.00292, n= 1.1024	0.6951	0.3565	0.5559
		45	a= 0.18862, c= 0.7476, k= 0.00886, n= 1.0331	0.6021	0.3502	0.5462

4.3.3 Simulation of drying process

The comparison between experimental moisture ratio at 35°C temperature conditions and that predicted by the Page model at same temperature conditions was shown in Figure 4.14. The predicated values agreed well with that obtained experimentally. This indicated that the drying process of hardened egg slices was well predicted and described by Page model. Therefore, Page's equation with respective constants is shown in equation 4.1 where k=0.0315, n=0.6716.

$$MR = exp\left(-kt^{n}\right) \qquad 4.1$$

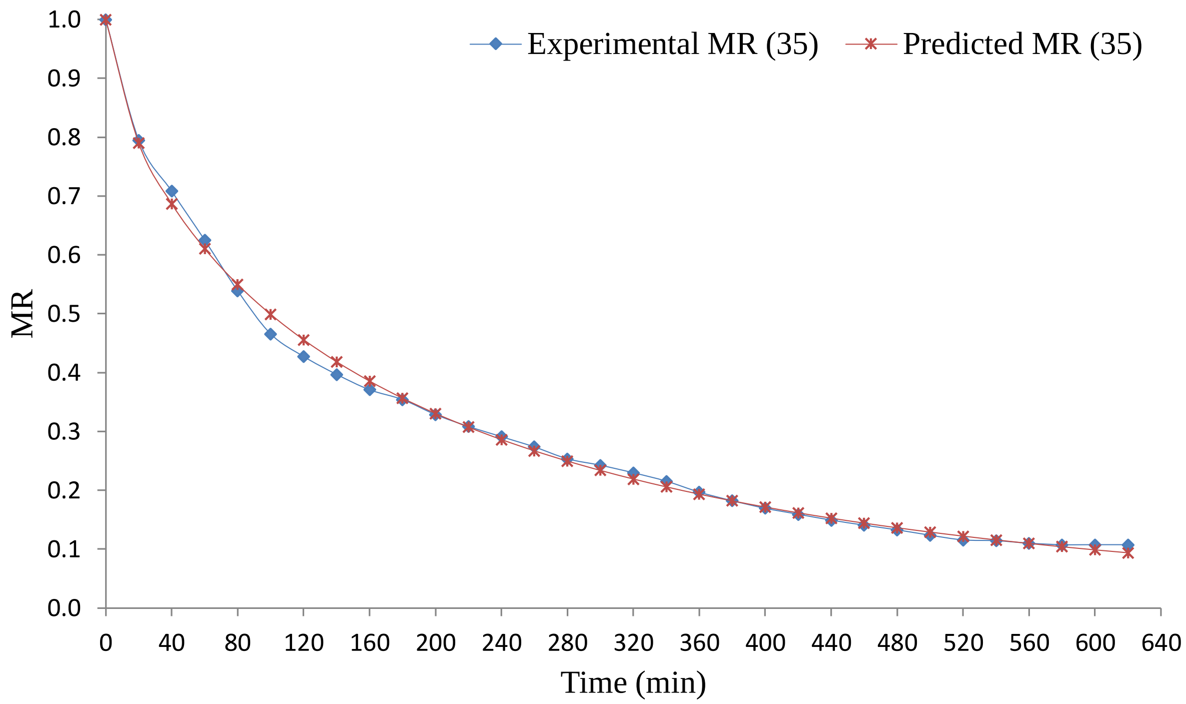

Figure 4.14: Page's predicted and experimental moisture ratio for eggs

Therefore, the consistency of Page model and drying constants is proved with R^2= 0.9991, x^2 = 0.0001, RMSE= 0.0012. This shows that moisture ratio of hardened egg at any time during thin layer drying process could be estimated more accurately by these expressions.

Figure 4.15 shows the correlation between experimental and predicted values of hardened egg drying process. There was a close banding at the final stages of drying attracting linear relationship with R^2 = 0.9973. This indicates agreement between the predicted and experimental values of moisture ratio. Thus, Page model accurately predicted the moisture ratio of hardened egg drying process under hot air forced convection drying.

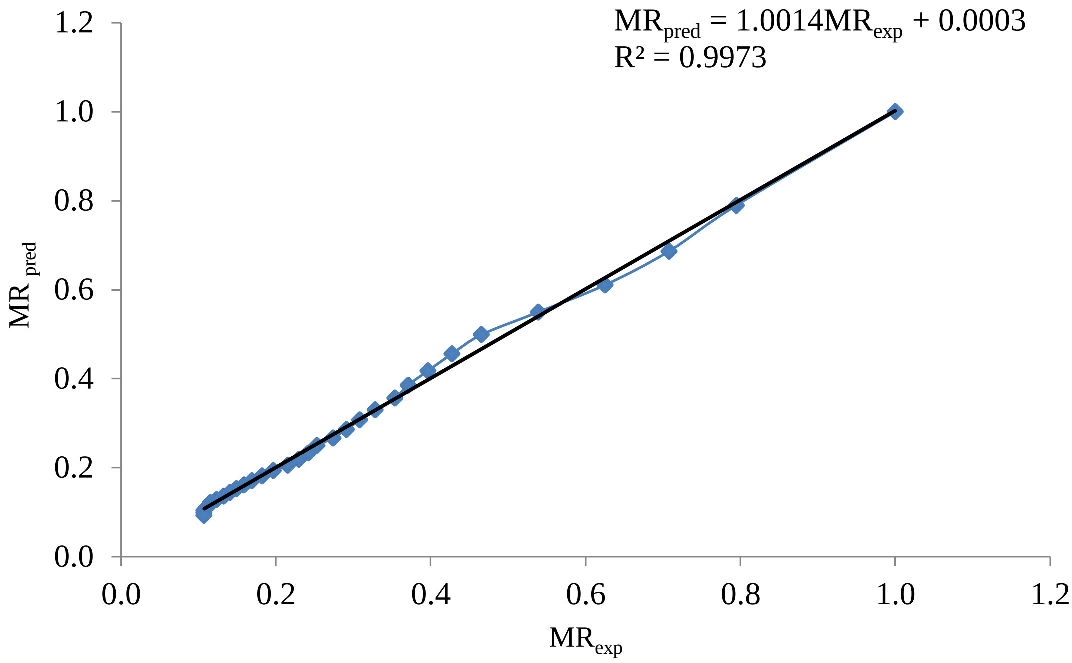

Figure 4.15: Predicted moisture ratios against experimental moisture ratio at 35^oC

Comparison of the moisture ratios predicted by Page model and experimental values for egg slices shows no distinct difference in the predicted and experimental moisture ratio values for the drying temperature condition.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

This study was conducted with the overall objective of determining the influence of varying drying airflow rate, temperature and slice thickness on egg drying rate and protein content under forced convection drying. The results demonstrated that forced convection drying was feasible in drying of eggs and the following conclusions were drawn.

a) Drying rate of hardened egg slices increased with airflow rate and temperature from 0.67 g/g min to 0.76 g/g min but decreases with increase in slice thickness (0.72 g/g min to 0.68 g/g min). Protein content decreased from 54.4% to 48.3% as airflow rate increased from 0.09 m^3/s to 0.15 m^3/s and decreased from 53.3% to 44.5% as temperature increased from 35 to 45°C. Protein content also increased from 47.9% to 53.8% as slice thickness increased from 10 mm to 30 mm.

b) Using Taguchi orthogonal array (L_9) for optimising drying process of eggs, the appropriate combinations of drying parameters are 0.15 m^3/s, 45°C and 10 mm. While for maximum protein content, 0.15 m^3/s, 35°C and 30 mm is the optimal drying condition for hardened eggs for the current research.

c) Page, Modified Page, and Aghbashlo et.al model appropriately described thin layer drying of hardened egg slices under forced convection with minimal deviations between experimental and predicted moisture ratios. However, Page model was more superior to the other two models with R^2 = 0.9991, x^2 and RMSE being 0.0001and 0.0012 respectively.

5.2 Recommendations

The recommendation made from the study is;

1. The highest drying rate for the egg slices were 0.15 m^3/s, 45^oC and 10 mm while for maximum protein content, 0.15 m^3/s, 35^oC and 30 mm were recommendable for industrial application especially in Kenya.

Further research on hardened egg drying can be done on:

1. The storage period of dried eggs at varying moisture content and other chemical composition to determine shelf-life of eggs at various moisture content;
2. Other thin layer drying models that were not used in the present research are used to predict how appropriate they compare the experimental and predicted drying data of eggs.

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APPENDICES

APPENDIX 1: LIST OF TABLES

Table A.1: Ambient experimental conditions

		Ambient conditions		Drying air Temperature		
				35°C	40 °C	45 °C
Day	Dry bulb Temp. (°C)	Wet bulb Temp. (°C)	Max. temp (°C)	%Relative humidity		
1	17.5	14.0	24.0	34.0	25.0	19.0
2	17.0	13.0	23.9	33.0	24.5	19.0
3	17.0	13.5	24.0	34.0	25.0	19.0
4	18.5	15.5	23.6	33.5	25.0	18.5
5	18.5	14.0	22.6	32.0	24.0	18.0
6	17.0	14.0	23.5	37.0	28.0	20.0
7	17.0	14.5	23.9	37.0	26.0	20.5
8	17.5	15.0	24.8	38.0	28.0	21.0
9	18.0	14.0	23.7	37.0	28.0	20.0
10	15.0	14.0	19.5	29.0	20.5	16.0
11	16.5	14.0	25.5	43.0	32.0	25.0
12	17.5	14.0	25.2	50.5	39.0	29.5
13	17.0	14.0	21.7	37.0	28.0	20.5
14	16.0	15.0	22.7	30.5	22.5	18.0
15	16.5	13.0	22.2	34.0	26.0	19.5
16	16.0	13.5	23.0	39.0	29.0	21.0
17	16.5	13.5	24.0	40.5	30.5	24.0
18	17.0	13.5	24.5	40.0	32.7	22.0

Table A.2: Summary of factor levels

Airflow rate (m^3/s)	Drying temperature (^0C)	Egg slice thickness (mm)
0.09	35	10
0.12	40	20
0.15	45	30

Table A.3: Drying rate optimisation of eggs using Taguchi technique

Experiment No.	Air flow rate (m³/s)	Temperature (^{0}C)	Thickness (mm)	Drying rate (g/g min)	Corresponding S/N Ratio (dB)
1	0.09	35	10	0.64	-6.08
2	0.09	40	20	0.67	-3.85
3	0.09	45	30	0.74	-3.79
4	0.12	35	20	0.67	-6.27
5	0.12	40	30	0.65	-6.07
6	0.12	45	10	0.67	-5.60
7	0.15	35	30	0.69	-4.91
8	0.15	40	10	0.80	-4.10
9	0.15	45	20	0.75	-7.69

Table A.4: Protein content optimisation using Taguchi technique

Experiment No.	Airflow rate (m³/s)	Temperature (^{0}C)	Thickness (mm)	Protein content (%)	Corresponding S/N Ratio (dB)
1	0.09	35	10	53.3	34.33
2	0.09	40	20	48.3	32.59
3	0.09	45	30	42.0	32.21
4	0.12	35	20	40.8	32.03
5	0.12	40	30	54.6	34.68
6	0.12	45	10	43.8	32.63
7	0.15	35	30	57.10	34.77
8	0.15	40	10	53.1	34.47
9	0.15	45	20	47.2	33.46

Table A.5: Two-way without replication ANOVA for temperature and airflow rate

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Temperature	75.2150	2	37.6075	19.1000	0.0090	6.9443
Flow rate	56.3857	2	28.1929	14.3185	0.0150	6.9443
Error	7.875926	4	1.9690			
Total	**139.4767**	**8**				

Table A.6: Two-way without replication ANOVA for temperature and thickness

Source of Variation	***SS***	***df***	***MS***	***$F_{computed}$***	***P-value***	***$F_{critical}$***
Temperature	138.0399	2	69.0200	5.1586	0.0781	6.9443
Thickness	91.4595	2	45.7297	3.4179	0.1363	6.9443
Error	53.5182	4	13.3795			
Total	**283.0176**	**8**				

Table A.7: Two-way without replication ANOVA for thickness and airflow rate

Source of Variation	***SS***	***df***	***MS***	***$F_{computed}$***	***P-value***	***$F_{critical}$***
Thickness	52.3842	2	26.1921	2.8227	0.1720	6.9443
Flow rate	57.8044	2	28.9022	3.1148	0.1529	6.9443
Error	37.1164	4	9.2791			
Total	**147.305**	**8**				

Table A.8: ANOVA for airflow rate after 120 min of egg drying

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***$F_{critical}$***
Airflow rates	0.0030	2	0.0015	0.0760	0.9273	3.8853
Residual error	0.2405	12	0.0200			
Total	0.2435	14				

Table A.9: ANOVA for temperature after 100 min of egg drying

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***$F_{critical}$***
Temperature	0.0018	2	0.0009	0.0336	0.9671	3.6823
Residual error	0.4031	15	0.0269			
Total	0.4049	17				

Table A.10: ANOVA for slice thickness after 140 min of egg drying

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*$F_{critical}$*
Slice thickness	0.0013	2	0.0007	0.1067	0.8999	4.2565
Residual error	0.0569	9	0.0063			
Total	0.0582	11				

Table B.1: The optimization experiment

Experiment No.	Airflow rate (m/s)	Drying temperature (^{0}C)	Egg layer thickness (mm)
1	0.09	35	10
2	0.09	40	20
3	0.09	45	30
4	0.12	35	20
5	0.12	40	30
6	0.12	45	10
7	0.15	35	30
8	0.15	40	10
9	0.15	45	20

Table B.2: Signal to Noise ratio of three parameters for drying rate

Level	Flow Rate (m^3/s)	Temperature (^{o}C)	Slice thickness (m)
1	-5.63*	-5.66	**-6.29**
2	-5.71	-5.78	-5.68
3	**-7.52**	**-7.42**	-5.74

** Signal to noise ratio (dB)*

Table B.3: Signal to Noise ratio of three parameters for proteins

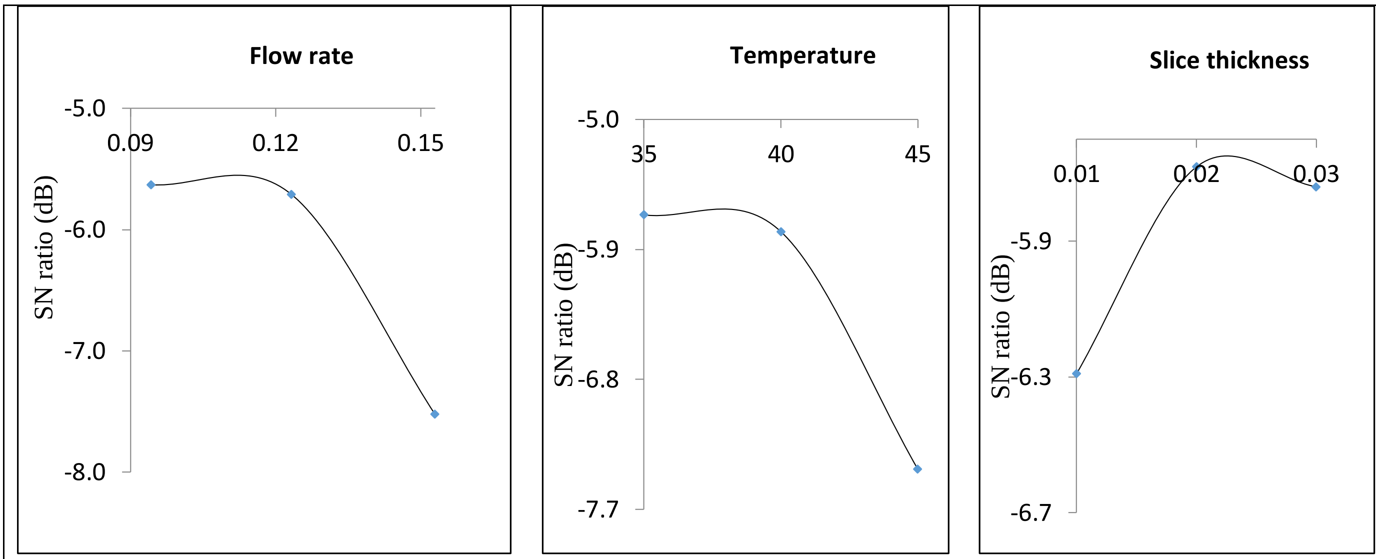
Level	Flow rate (m^3/s)	Temperature (^{o}C)	Slice thickness (mm)
1	33.70*	**34.27**	34.06
2	33.48	34.24	33.23
3	**34.64**	33.31	**34.39**

** Signal to noise ratio (dB)*

Table C.1: Mean Moisture ratios for Page Model data at various temperatures

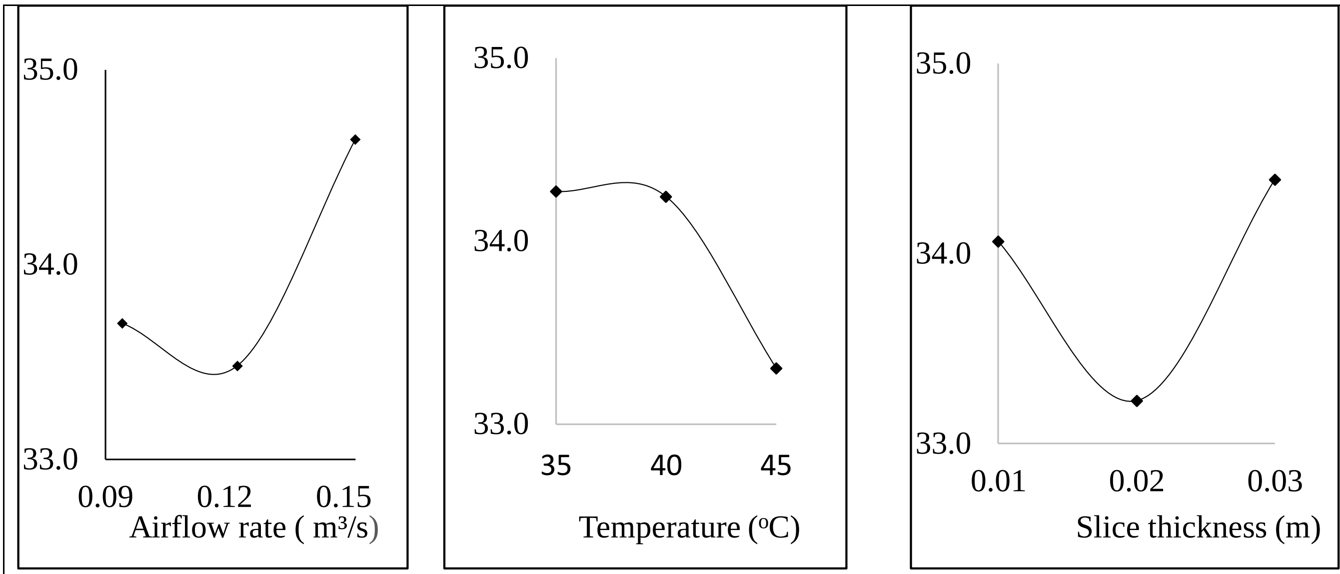
	Temperature					
	35°C		40°C		45°C	
TIME (min)	MR experimental	MR predicted	MR experimental	MR predicted	MR experimental	MR predicted
0	1.00	1.00	1.00	1.00	1.00	1.00
20	0.80	0.79	0.88	0.90	0.87	0.90
40	0.71	0.69	0.80	0.82	0.79	0.80
60	0.63	0.61	0.75	0.74	0.70	0.71
80	0.54	0.55	0.68	0.68	0.63	0.62
100	0.47	0.50	0.63	0.62	0.57	0.55
120	0.43	0.46	0.58	0.57	0.52	0.49
140	0.40	0.42	0.55	0.52	0.46	0.43
160	0.37	0.39	0.51	0.48	0.41	0.38
180	0.35	0.36	0.46	0.44	0.37	0.33
200	0.33	0.33	0.43	0.40	0.33	0.29
220	0.31	0.31	0.40	0.37	0.28	0.25
240	0.29	0.29	0.36	0.34	0.26	0.22
260	0.27	0.27	0.35	0.31	0.22	0.19
280	0.25	0.25	0.31	0.29	0.19	0.17
300	0.24	0.23	0.28	0.26	0.17	0.15
320	0.23	0.22	0.25	0.24	0.13	0.13
340	0.22	0.21	0.23	0.22	0.11	0.11
360	0.20	0.19	0.20	0.21	0.11	0.10
380	0.18	0.18	0.18	0.19	0.08	0.09
400	0.17	0.17	0.17	0.17	0.08	0.08
420	0.16	0.16	0.15	0.16	0.08	0.07
440	0.15	0.15	0.13	0.15	0.06	0.06
460	0.14	0.14	0.12	0.14	0.04	0.05
480	0.13	0.14	0.11	0.13	0.02	0.04
500	0.12	0.13	0.10	0.12	0.02	0.04
520	0.12	0.12	0.10	0.11	0.02	0.03
540	0.11	0.12	0.09	0.10	0.02	0.03
560	0.11	0.11	0.08	0.09		
580	0.11	0.10	0.08	0.08		
600	0.11	0.10	0.08	0.08		
620	0.11	0.09				

APPENDIX 2: LIST OF FIGURES



a) Airflow rate (m³/s)   b) Temperature (°C)   c) Thickness (m)

Figure A.1: Optimised drying rate parameters with respective signal to noise ratio



a) Airflow rate (m³/s)   b) Temperature (°C)   c) Thickness (m)

Figure A.2: Optimised protein content parameters with respective signal to noise ratio

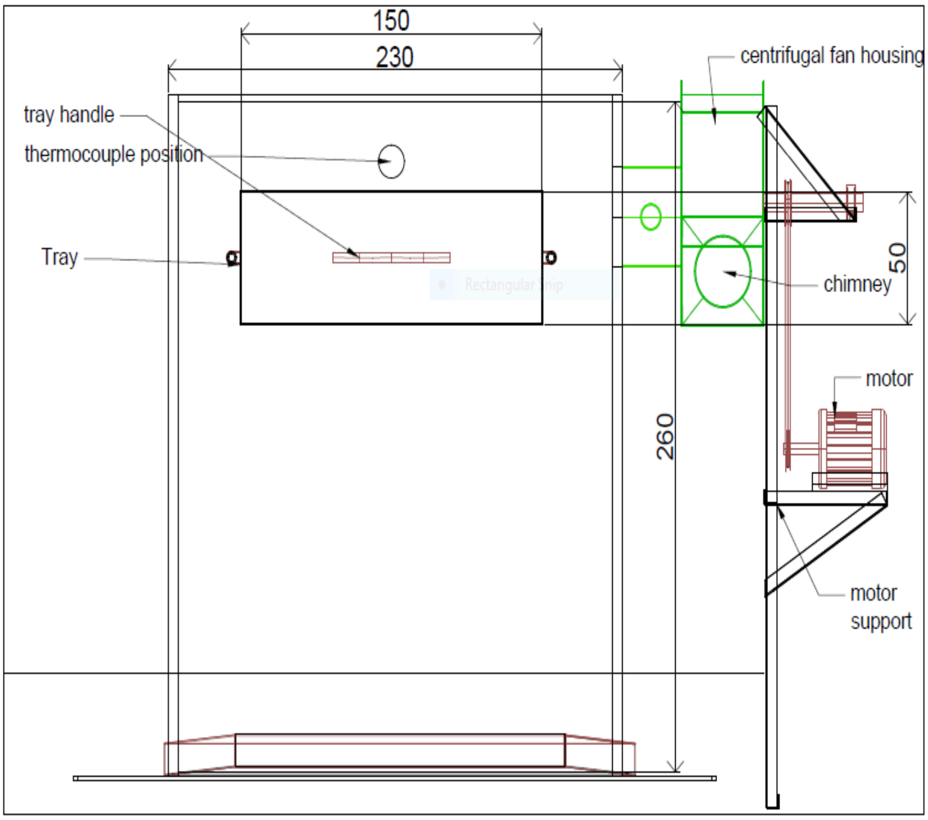


Figure A.3: The back view of the forced convection dryer

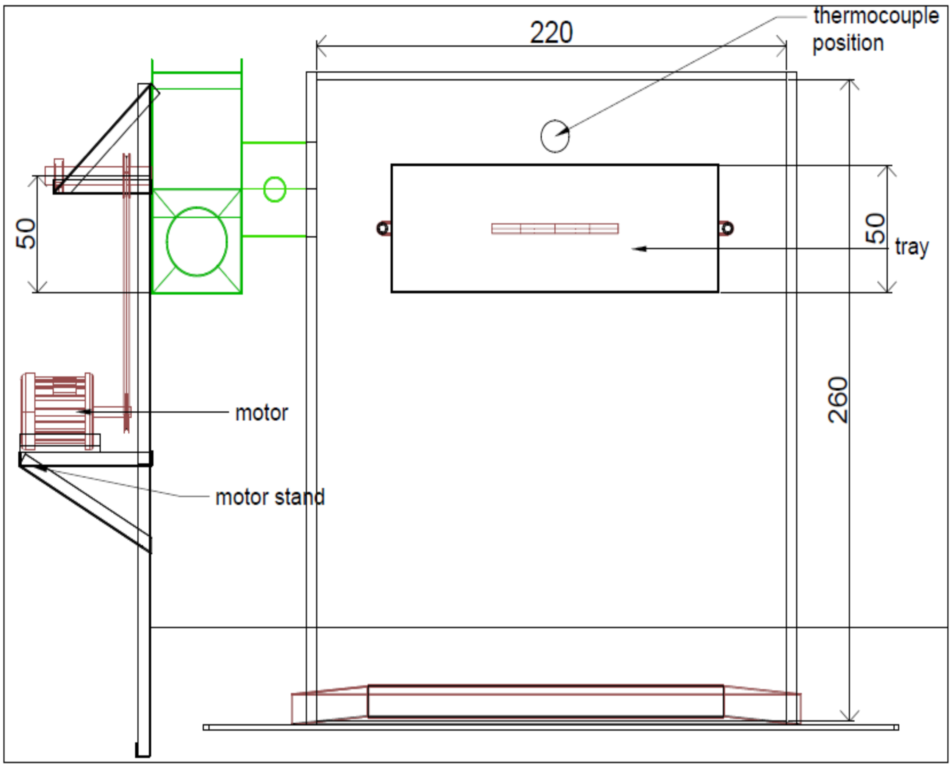


Figure A.4: Front view of the forced convection dryer

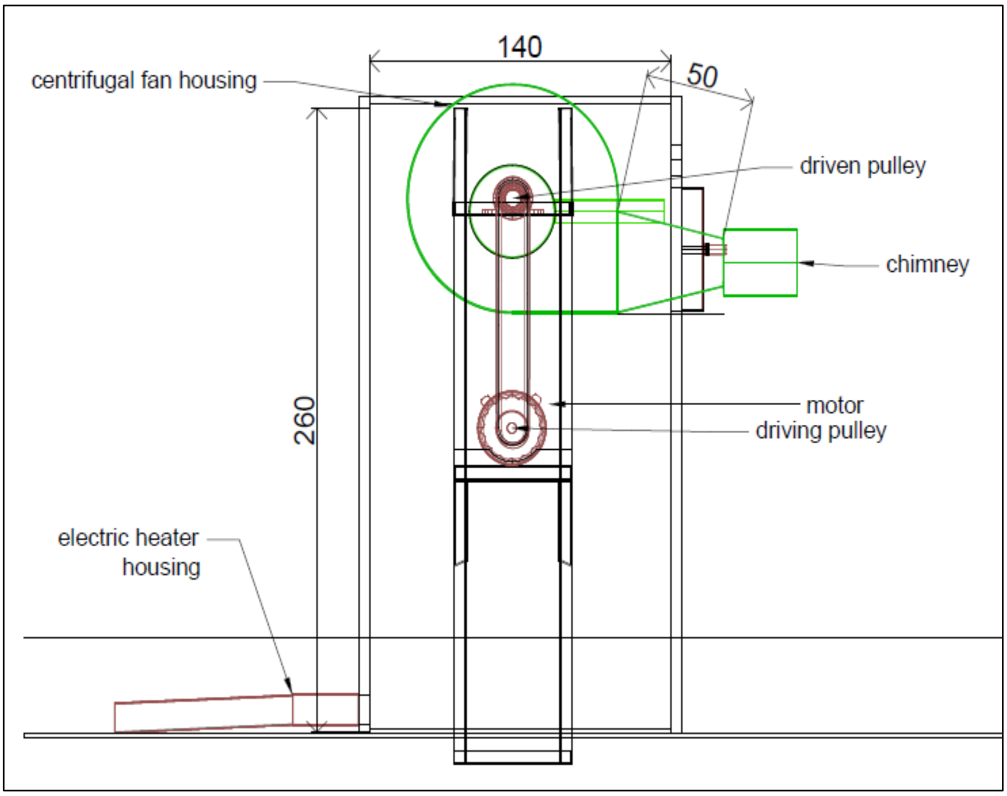


Figure A.5: Left view of the forced convection dryer

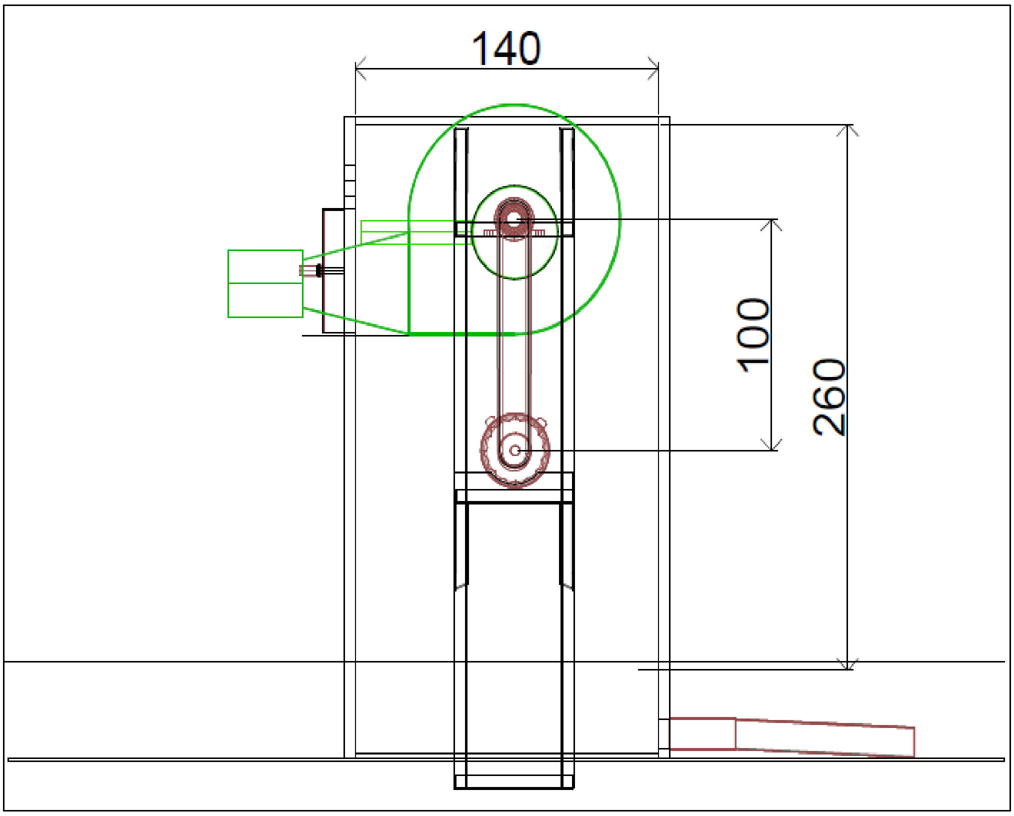


Figure A.6: Right view of the forced convection dryer

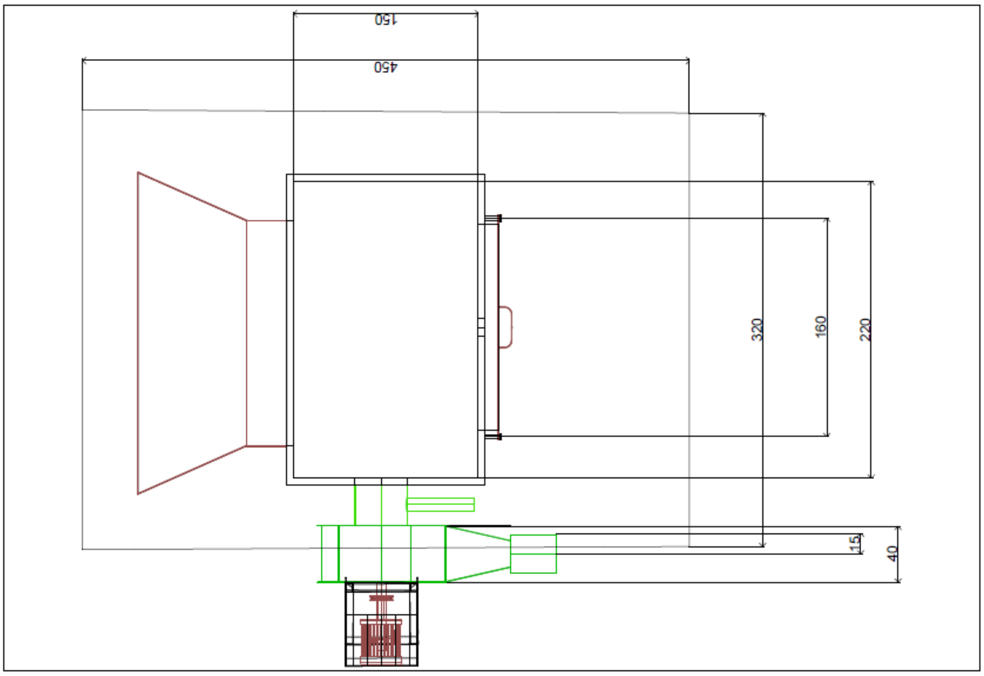


Figure A.7: Top view of the forced convection dryer

APPENDIX 3: LIST OF PLATES

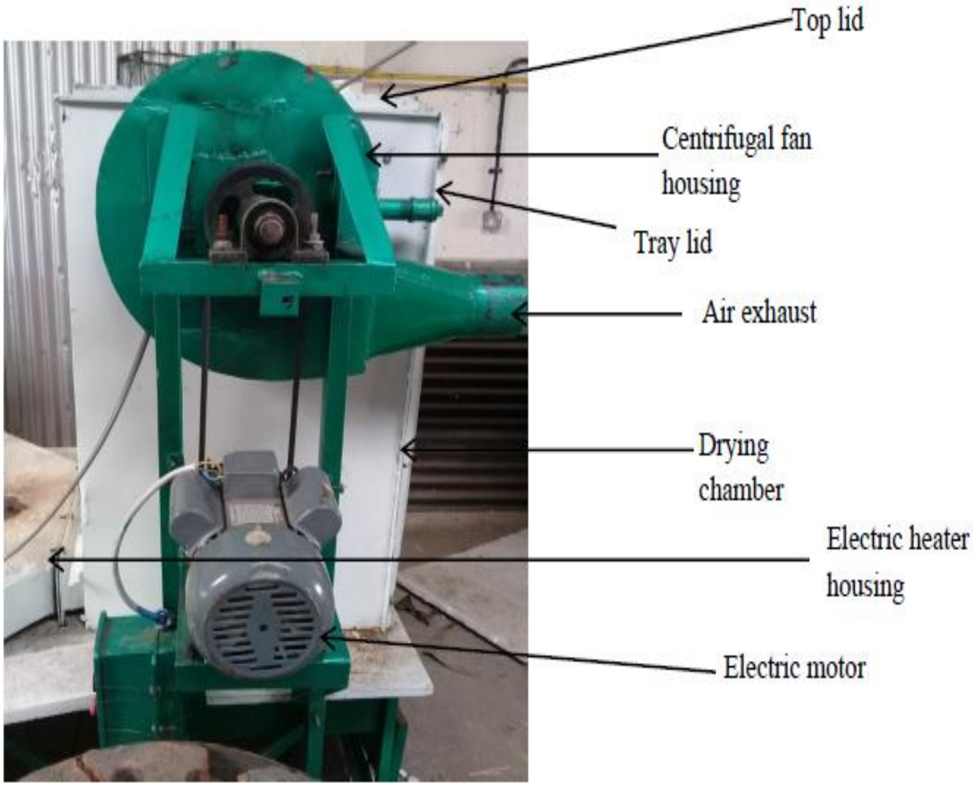


Plate A.1: Experimental siphoning type forced convection dryer

Plate A.2: Sliced egg samples in a tray ready for drying process

Plate A.3: Temperature controlling using P.I.D set up in progress

Plate A.4: Mass measurements using digital weighing balance (precisa310M).

Plate A.5: Samples of dried egg slices

APPENDIX 4: LIST OF PUBLICATIONS AND CONFERENCE PAPERS

S/No	Description of the article
1.0	Mecha, P., Nyaanga, D. M. and Njue, M. R. (2018a). Forced convection hot air drying of hardened egg slices. *International Journal of Scientific & Technology Research,* 7(4): 251-259.
2.0	Mecha, P., Nyaanga, D. M. and Njue, M. R. (2018b). *Optimisation of hardened egg drying process using a forced convection system*. Paper presented at the 12th Egerton University International Conference, Egerton University.