INFRARED DRYING OF BILTONG: EFFECT OF PRE-TRATMENT AND DRYING CONDITIONS ON THE DRYING CHARACTERISTICS AND PRODUCT QUALITY

K Cherono

LITERATURE REVIEW AND PROJECT PROPOSAL

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School of Engineering
University of KwaZulu-Natal
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ABSTRACT

Drying of biltong as a product is of traditional and commercial importance in South Africa. Biltong is commonly dried using conventional hot air (HA) systems which pose food safety and quality challenges. Commercial and middle level producers use improved versions of gas fired and electric heaters to dry biltong but these systems have low energy efficiencies.

Infrared drying is understood to be a novel drying technology with numerous benefits from a food quality, safety and energy efficiency standpoint that can achieve simultaneous drying and deactivation of fungal and bacterial spores. Infrared dried biltong therefore as a ready to eat meat based snack will be a premium product with lower production costs giving the health conscious consumers quality products and profits to food processors.

Drying of biltong is an intricate process with different factors coming into play that have to be understood for the process to be successfully carried out.

In the proposed study, two infrared heaters with intensities of 1000–5000 $W.m^{-2}$ and surface temperatures of 700–1200^{o}C are used to investigate the effects of product thicknesses (5mm – 15mm), pre-treatment duration (6–24 hours) and heater spectral characteristics on the dying kinetics and the product quality. Infrared drying data will be fitted into five commonly used drying models and their goodness of fit assessed based on their R^2 and RMSE values. Quality analysis through colour changes, textural analysis, rehydration and shrinkage of the infrared dried samples will be carried out and compared to the HA dried control samples dried in a climate controlled chamber at 25^{o}C and 60% RH.

The proposed study will give insight into the infrared drying behaviour of biltong and indicate the most important drying parameters that affect the product. This will serve as a guide to biltong processors to produce high quality products through optimized processes.

PREFACE

I, Kipchumba Cherono declare that

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1. INTRODUCTION

Drying of food and agricultural commodities is an important undertaking carried out as a preservation measure or as a means for conditioning products for further processing and handling steps. In engineering terms, drying of food and agricultural products is understood as a simultaneous heat and mass transfer process (Afzal and Abe, 2000) that aims at reducing the moisture of food products in order to lengthen their shelf life as well as allow for other processing and handling steps to be carried out. Subsequent food and agricultural processing operations to this effect therefore, depend heavily on the success of drying.

Different drying technologies have emerged alongside the traditional sun drying technologies due to the advancement in research in food and crop drying. Solar drying of agricultural and food products uses solar energy to heat up products by combining the processes of conduction and convection to achieve moisture reduction (Khir et al., 2006).

Sun drying is the oldest food drying technology and it involves spreading of products in layers on a flat surface that is exposed to the sun's rays. Solar drying evolved from sun drying where attempts to capture and concentrate the sun's radiation on the food to be dried are explored. Solar dryers consist of three basic parts; a collector, drying chamber and an air duct system (Green and Schwarz, 2001). Configurations of solar dryers include direct solar dryers, indirect mode solar dryers, mixed mode solar dryers and hybrid solar dryers. Hybrid types combine solar heating with an additional heating source such as biomass or fossil (Bhattacharya et al., 2000; Murthy, 2009; Fudholi et al., 2010). Different configurations of hybrid solar dryers have been discussed in detail by Fudholi et al. (2010).

Spray drying constitutes drying systems that are used to dehydrate slurries and purees, (Vega-Mercado et al., 2001; Gharsallaoui et al., 2007) where drying is achieved by spraying the liquid to be dried in a hot medium, normally air. Fluidized bed drying is similar to spray drying except for this case the solid food is dried in a stream of hot air in which they are suspended and conveyed (Vanecek et al., 1966; Vega-Mercado et al., 2001; Syahrul et al., 2002).

Freeze drying and osmotic drying are drying technologies used to dry high value products. Freeze drying comprises of a freezing process and a sublimation step (King, 1971). Osmotic drying utilizes differences in product concentration to dry them which in some cases is aided by a vacuum (Vega-Mercado et al., 2001). Drying technologies that comprise of high vacuum systems, microwaves and radio frequency are some of the drying methods or technologies still under development (Goullieux and Pain, 2005; Pereira and Vicente, 2010)

Drying is an energy demanding process. Statistics (Mujumdar and Devahastin, 2000) show that in Canada, USA, France and UK, drying consumes 10-15% of the total national industrial energy demand as well as 20-25% of the total national industrial energy demand for Denmark and Germany. Convective drying systems comprise of 85% of all industrial drying systems (Raghavan et al., 2005). Convective systems have low drying efficiencies as their biggest limitation due to convective losses in heating and transportation of the working fluid. With emerging global environmental challenges, courtesy of greenhouse gas emissions, there is an urgent need for energy intensive processes such as drying to evolve to the extent that every joule of drying energy is efficiently harnessed (Madamba et al., 1996; Mujumdar and Devahastin, 2000; Raghavan et al., 2005).

Alternative drying technologies have been developed with maximizing energy efficiency as the objective through the research efforts in different engineering disciplines. Some of the emerging drying technologies include sonic assisted drying, super-heated steam drying, heat pump assisted drying and electro assisted technologies (Goullieux and Pain, 2005; Raghavan et al., 2005; Pereira and Vicente, 2010; Rastogi, 2012). Radiative heating using infrared (IR) energy has given promising results and there are currently huge interests in its application for drying food and agricultural materials.

Infrared radiation is electromagnetic radiation produced by any object above the temperature of absolute zero degrees (Krishnamurthy et al., 2008; Jun et al., 2011) and can be used to dry food and agricultural products. Some of the distinct advantages infrared drying has over conventional hot air drying include the production of high quality products, high energy efficiency, high heat transfer rates and reduced drying time (Krishnamurthy et al., 2008; Rastogi, 2012). The advantages of infrared drying can be summarized as follows: Infrared drying results in energy savings from improved drying efficiencies (Nowak and Lewicki, 2004; Basman and Yalcin, 2011; Ponkham et al., 2012), equipment used is compact (Nowak and Lewicki, 2004), there is a high efficiency of heat transfer through air or vacuum (Nowak and Lewicki, 2004; Sharma et al., 2005a; Shih et al., 2008; Basman and Yalcin, 2011; Khir et al., 2011; Ponkham et al., 2012), it has good prospects for automation (Nowak and Lewicki, 2004) and has improved hygiene (Nowak and Lewicki, 2004). In the same vain, the aspect of this technology being environmentally friendly because of the elimination of waste heat in food processing makes it an attractive choice (Khir et al., 2011).

As an emerging discipline, research has been carried out on its application for drying different products. However, due to the nature and complexity of the composition and behaviour of food and agricultural materials, the application of research results carried out on a given product may not give valid conclusions for a different product. In addition, every food and agricultural material has unique characteristics. Understanding the of behaviour of a product under infrared drying will confer the benefits of confidence in the design of a given drying system and allow for the scaling up of these designs to suit the high volumes of products processed in industrial settings.

Biltong is a meat based snack that is very popular in South Africa. Different recipes are used for its preparation but it commonly undergoes a drying process after being spiced and salted. There are few published articles on the drying of biltong and most producers of biltong for house consumption usually utilize ambient conditions for drying their products. Electric heaters are also used by some of the middle level processors who supply their products to supermarkets and other retail outlets. These constitute conventional hot air drying methods that utilize heated air to dry the product. These drying methods require long drying times and pose serious questions to the food quality of biltong (Nortjé et al., 2005).

Currently, there are no publications on infrared drying of biltong. The successful application of infrared drying to biltong will dramatically reduce the drying time and will also address some of the food quality issues that often result when drying biltong using conventional hot air methods. These issues relate to microbial and enzymatic deactivation that affects the shelf life and safety of conventionally processed biltong (Nortjé et al., 2005; Burnham et al., 2008; Naidoo and Lindsay, 2010). There is therefore the need to understand the parameters that influence infrared drying of biltong to enable the drying process to be optimized resulting in high quality products and reduced energy costs.

The proposed study therefore undertakes to characterize the drying kinetics of biltong under different peak emission characteristic wavelengths. The food quality of infrared dried biltong will be compared to that of conventionally dried biltong. Product quality changes of infrared dried biltong will be assessed with respect to the product thickness, spicing level, heater wavelength and emission spectrum.

2. LITERATURE REVIEW

This chapter discusses some of the important aspects of literature by giving a background of the concepts and theoretical considerations on the subject matter and forms the basis for the methodologies adopted in this study.

2.1 Overview of Drying of Food and Agricultural Materials

Drying is one of the oldest and widely used process in many engineering disciplines and applications. The process is used in diverse fields and industries including chemical, agricultural, biotechnology, paper and pulp, pharmaceutical, mineral mining and processing, polymers, metals and wood products manufacturing processes (Mujumdar and Devahastin, 2000). Different definitions and descriptions of drying have been widely discusses in literature.

Mujumdar and Devahastin (2000) described drying as a process that converts solid, liquid or a semi-solid feedstock into a solid material through the evaporation of the liquid into vapour by application of heat. In other applications such as freeze drying, heat is supplied and it directly causes drying through sublimation. This definition does not include some special drying operations such as evaporation in cases where semi-solid media need to be concentrated, mechanical water removal processes which includes centrifugation, filtration, sedimentation, drying of gases and liquids using molecular sieves or extraction (Mujumdar and Devahastin, 2000). Toğrul (2005) described drying as a process for the removal of most of the water contained in a product or a material. Ilic and Turner (1986) defined drying as a process involving simultaneous heat and mass transfer in which heat is supplied by an external source that evaporates and subsequently reduces moisture from a wet porous medium. McMinn and Magee (1999) described drying as a moisture removal process from solids and constitutes an integral element in food processing. They further qualified drying as a recognized and organized field of research in chemical engineering. Jangam and Mujumdar (2010) defined drying as one of the economical means of preserving foods of all manner in which water is removed by the application of heat. They further described it as a complex operation that involves transient transfer of mass and heat along with several rate processes that includes chemical or physical changes which may bring about product quality changes.

Drying therefore, from these descriptions and definitions can be termed as a heat and mass transfer process that is used to reduce the moisture in different materials. It is a food preservation tool and has huge importance in food processing and handling.

The role of drying food has been described by Green and Schwarz (2001) as a process that minimizes food spoilage and is ideal for fruit preservation due to their high acid and sugar content. Mwithiga and Olwal (2005) in their study of drying kales in Kenya described drying of this vegetable as an important process that improves its storability for long periods of time without appreciably affecting the nutritive elements. Drying of vegetable products reduces their weight and therefore helps considerably in making their handling and haulage convenient (Mwithiga and Olwal, 2005). They also indicated that drying of this vegetable confers the benefit of product size reduction hence minimizes space and storage requirements as well as reducing price fluctuations in the market by ensuring continuous supply when the crop is out of season (Mwithiga and Olwal, 2005).

Fudholi et al. (2010) discussed some of the reasons for drying of food and agricultural products. They described drying as an important post-harvest food handling operation which can lengthen the shelf life of harvested products, improve its quality and empower the farmer through the provision of a better bargaining ground by maintaining relatively constant prices for the products as well as the reduction of post-harvest losses. Drying of food also brings about the reduction of transport costs by the removal of the excess water from the products (Fudholi et al., 2010).

Mujumdar and Devahastin (2000) summarized some of the benefits of drying as follows: convenience in handling materials, preservation and storage, reduction in cost of transportation and enhancement of the quality of dried product.

Jangam and Mujumdar (2010) described drying as a process that mainly proposes to reduce or completely eliminate microbial activity in food materials which can occur during harvesting operations and storage, with the microbial agents commonly present in food being bacteria, protozoa and fungi. Insects also contribute in many ways to food losses. Food drying reduces or eliminates enzymatic browning and lipid oxidation (Jangam and Mujumdar, 2010).

Food and crop drying from the foregoing discussions is therefore one of the most important tools used by mankind since ancient times and has enabled civilizations to exist and evolve to date. Without food drying, its preservation, handling and subsequent processing operations could be difficult or even impossible, bringing with it serious challenges on food availability.

2.1.1 Terminologies and fundamentals

Every industry has its own terminology, fundamental principles and applicable technical jargon. The forthcoming discussion highlights some of the important terminologies relevant to drying of food and agricultural materials.

Moisture content is the single most important measure that shows how much water is in a food material. It is presented in terms of dry basis or wet basis which are abbreviated as d.b and w.b, respectively. The wet basis moisture is normally used in commercial applications while dry basis is used for engineering and research purposes. Toğrul (2005) calculated the moisture content of apple samples using equation 2.1.

$$M=\frac{W_0 - W - W_1}{W_1} \qquad 2.1$$

where M is the moisture content of the product in g of water/kg of dry solid, W_0 is the initial weight of the sample, W the weight of the water evaporated and W_1 the weight of the dry matter in the sample.

Khir et al. (2006) described the moisture content of rough rice as one of the most important factors that influence its storage, further handling and the resultant quality. For this reason, rough rice has to be adequately dried to safe storage moisture levels.

Equilibrium moisture content is described by Mujumdar and Devahastin (2000) as the moisture content of a wet solid material in equilibrium with the surrounding air at a given relative humidity and temperature. A plot of equilibrium moisture content verses relative humidity at a certain temperature is called a sorption isotherm and is as shown in Figure 2.1. If a product is put under a set of humidity and temperature condition, it will absorb or lose water from or to the ambient air depending on the hygroscopic nature of the product.

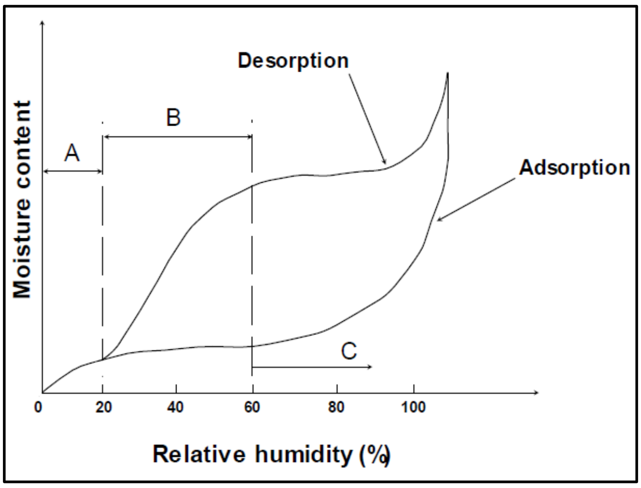

Figure 2.1 A typical sorption isotherm for a food material (McMinn and Magee, 1999)

From Figure 2.1, the concept of hysteresis where food materials do not have identical curves in both adsorption and desorption cycles is illustrated. Sections A, B and C are described by Jangam and Mujumdar (2010) as unique zones that describe the water binding characteristics within different areas in the solid matrix. They described section A as an area which water is tightly bound, B as that which water is less bound and C as an area where water is loosely held in the capillaries of the solid mass.

Water activity of food materials is indicative of the shelf life and storability of moist food products. Jangam and Mujumdar (2010) described water activity as an important indicator for assessing the availability of water for the growth of microbes in food material, the germination of their spores and the participation of this water in a number of chemical reactions. They defined water activity as the ratio of the partial pressure of water over the wet food material to that of equilibrium vapour pressure of the water contained in the food material at a constant temperature and is presented by equation 2.2.

$$a_w = \frac{P}{P_w} = \frac{RH_{eq}}{100} \tag{2.2}$$

where a_w is the product water activity, P is the partial pressure of water in the food material P_w the equilibrium vapour pressure and RH_{eq} the equilibrium relative humidity.

Models that give expressions of a_w have been described in literature. Some include Langmuir equation, Oswin equation, Halsey equation, mosified Handerson equation and Chung-pfrost equation (Mwithiga, 2007). Jangam and Mujumdar (2010) gave the minimum water activity in foods for the growth and survival of different microorganisms as presented in table 2.1. Therefore, any relative humidity that is lower than these values will not be conducive for the growth of the particular microbe.

Table 2.1 Minimum water activities for the survival of different microoganisms (Jangam and Mujumdar, 2010)

Micro-organism	Water activity
Organisms producing slime on meat	0.98
Pseudomonas, Bacillus cereus spores	0.97
B. subtilis, C. botulinum spores	0.95
C. botulinum, Salmonella	0.93
Most bacteria	0.91
Most yeast	0.88
Aspergillus niger	0.85
Most molds	0.80
Halophilic bacteria	0.75
Xerophilic fungi	0.65
Osmophilic yeast	0.62

Water activity influences the quality, safety, shelf life, texture and flavour of food. Controlling relative humidity is equivalent to controlling food spoilage in most cases (Jangam and Mujumdar, 2010). Temperature for instance varies water binding characteristics, water dissociation, solubility of solutes or the condition of food matrix. Therefore, water activity is a function of food temperature and is product specific (Jangam and Mujumdar, 2010). The measurement of water activity in different food products has been described by different authors (Prior, 1979; Slade et al., 1991; Hamanaka et al., 2006) . Nortjé et al. (2005) carried out proximate analysis of biltong during gamma irradiation. They used water activity as one of the parameters used to measure the microbial safety of biltong using a Navosina Thermoconstanter TH-2 water activity meter at 25^{o}C. The water activity of the moist beef biltong was found to be 0.919. Yang et al. (2013) measured the water activity of dry roasted almonds using a water activity meter of type Aqua lab model CX-2. In their study, they found that water activity values of 0.2- 0.3 produced almonds that had the maximum shelf life.

The moisture ratio of food is described to be a property dependent on moisture content of a food sample. It is commonly used to characterize the drying kinetics of biological products.

Yi et al.(2010) used a simplified version of moisture ratio equation during infrared drying of apple slices as presented by equation 2.3.

$$MR= \frac{M_t}{M_0} \quad (2.3)$$

where MR is the product moisture ratio (dimensionless) M_t is the moisture content in dry basis and M_0 is the initial moisture content in dry basis.

Celma et al. (2009) presented the moisture ratio equation during infrared drying of industrial wet grape residue using equation 2.4.

$$MR= \frac{M_t - M_e}{M_0 - M_e} \quad (2.4)$$

where MR and M_t are as defined earlier in equation 2.3 and M_e is the equilibrium moisture content.

They however simplified equation 2.4 to equation 2.3 since it is widely described in literature as the MR equation which governs the infrared drying of biological products (Toğrul, 2005; Shi et al., 2008; Yi et al., 2010; Khir et al., 2011)

The drying rate (D_R) is described in literature as the amount of water removed from a product per unit time (Jangam and Mujumdar, 2010). It is calculated using equation 2.5 as suggested by Kaya et al. (2007).

$$D_R= \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (2.5)$$

where $M_{t+\Delta t}$ is the moisture content of the products after elapsed drying time, Δt. M_t and D_R are as defined earlier.

2.2 Food Drying Technologies

Food drying technologies continually evolve and range from hot air methods to non-contact methods. A brief review of these is given in subsequent subheadings.

2.2.1 Sun and solar drying

Sun drying is the oldest food preservation method available in which sunlight is used to dry food materials by spreading it in layers on an open surface and exposing it to sunlight. Water from the food is lost through convective and conductive heat transfer. Natural sun drying comes with numerous challenges. Murthy (2009) summarized some of the shortcomings of sun drying of food materials as failure of the product to dry uniformly due to varying sunlight, low efficiencies and hence prolonged drying which could bring aflatoxin or microbial contamination, contamination by birds and debris brought by wind as well as insect infestation. Solar driers are designed to eliminate or minimize some of the drawbacks presented by sun drying. Solar drying therefore results in products whose quality is remarkably improved.

Different configurations of solar dryers exist. Classification of solar dryers has been described in different literature. Green and Schwarz (2001) discussed in detail the different classification of solar dryers as direct solar dryers, indirect solar dryers, mixed mode solar dryers and hybrid solar dryers. Murthy (2009) classified commonly used solar dryers in the Asian pacific as natural convection cabinet types, forced convection indirect type and greenhouse solar dryers. The construction of these dryers, their common uses and possible alterations to make them more efficient were discussed in detail by (Murthy, 2009).

Vega-Mercado et al. (2001) has categorized dryers into four generations of dryers. They described first generation dryers as cabinet and bed type that use heated air to dry the products. These dryers are suitable for drying food materials that are solid in nature. The second generation are those that are more suitable for dehydration of purees and slurries. They include spray dryers and drum dryers and they can be used to produce dehydrated powders and flakes. The third generation dryers include freeze dryers and vacuum dryers. These methods are important in preventing structural changes that occur in food materials during drying thus affecting the food quality. The fourth generation dryers are technologies that constitute high vacuum dying, fluidization, use of microwaves, reflectance window and radio frequency (RF). These methods are product specific and they are used depending on the nature and the quality attributes of the end product.

2.2.2 Freeze drying

Freeze drying technologies are used primarily for drying and preservation of high value products. Vega-Mercado et al. (2001) described freeze drying as a drying technology used to overcome the structural changes that occur due to product shrinkage as well as overcome the challenges that can occur due to losses in aroma compounds and flavour during drying. Ratti (2001) summarized freeze dying as a method for dehydrating high value food products (those which may be seasonal and perishable due to their limited availability, baby food which require that they maintain maximum nutrient levels, nutraceutical foods, unique organoleptical foods such as aromatic herbs and spices or special high end foods such as those used in the military) where a sublimation based dehydration method is used on a frozen product that adequately manages the microbial and enzymatic deterioration problems due to the low temperatures involved hence guaranteeing a high quality product. Generally, freeze drying involves high costs that make it prohibitive in its application. Freeze drying is often aided by a vacuum system.

2.2.3 Spray drying

Spay dried products mainly constitute powders and flakes. Vega-Mercado et al. (2001) and Gharsallaoui et al. (2007) characterized spray drying technology as a drying technique that involves the atomization of food material as it is passed into the drying chamber as well as drying by spraying it continuously onto a hot drying medium. They described the advantages of spray drying as a technique that can be easily automated; the resultant powder of the dried product is consistent in size if the dryer conditions are held constant as well as a method which is versatile with a wide range of equipment available.

2.2.4 Osmotic dehydration

Osmotic dehydration is described by Vega-Mercado et al. (2001) as a drying method in which water is removed from a food product by means of an osmotic gradient. It involves immersing a product in a hypertonic solution and water removal from the product is normally vacuum aided.

Rastogi et al.(2002) discussed in detail the factors that the rate of water removal in osmotic dehydration depend on. They presented these as the concentration of osmotic solution, its temperature, product size and geometry, agitation and magnitude of solution to dry matter.

2.2.5 Electromagnetic/Non-contact technologies

Non-contact methods are drying technologies that do not use a heated medium as a means of heat transfer. The common technologies that fall under this category are the electromagnetic radiation sources such as microwave systems and infrared heaters. These systems achieve high energy efficiencies due to reduced heat losses. Vega-Mercado et al. (2001) described the mechanism of microwave heating as a process that takes place due to molecular and atomic polarization that occurs in the food mass when exposed to microwaves through the rotation of molecules at high speed in an effort to align with polarity changes in the present electromagnetic field. This rotation causes friction with other molecules resulting in heat energy generation as presented in equation 2.6.

$$P = 1.41 f \left(\frac{E}{d}\right)^2 \varepsilon' \tan\delta \times 10^{12} \qquad (2.6)$$

where P the heat generated in watts, f is the frequency of electromagnetic field, E the voltage, d the distance between electrodes, ε' the product dielectric constant and tan δ the loss tangent.

Infrared radiation is also used as heating source for drying food materials. This technology is the subject of this research and is discussed in chapter 2.3.

2.2.6 Emerging technologies

Drying technologies evolve with changes in the existing food drying needs. Improvements on the existing technologies are also made continually (Pereira and Vicente, 2010; Vishwanathan et al., 2013).

Emerging food drying technologies include electro technologies, sonic assisted drying, super-heated stem drying (Raghavan et al., 2005) as well as ohmic heating (OH)(Goullieux and Pain, 2005; Pereira and Vicente, 2010). Electro technologies (Raghavan et al., 2005) comprise of drying methods that use electromagnetic waves such as RF and microwaves that heat up the food mass directly without heating the surrounding matter. These methods have huge energy savings (Geveke, 2005) and good prospects for industrial application. Heat pump assisted drying applies the principles of refrigeration to cool and condense water out of air and is a method with very low operational costs compared to direct oil heaters, gas fired heaters or electrical heaters (Raghavan et al., 2005; Hawlader et al., 2006). Super-heated steam drying uses super-heated steam to dry and remove water from food products (Raghavan et al., 2005). Sonic assisted drying involves the use of low frequency sound (20-40 KHZ) to dry products in combination with other drying methods such as conventional hot air method and has improved energy efficiencies when used with other drying methods (Raghavan et al., 2005). OH involves the passage of an alternating current through food products and by virtue of its electrical resistance; heat is internally generated within the food material (Pereira and Vicente, 2010).

2.2.7 Challenges of conventional drying methods

Conventional hot air food drying technologies are considered to involve the use of hot air as the drying medium. Direct sun drying is a food drying method with huge limitations in its application as discussed in literature (Green and Schwarz, 2001; Murthy, 2009; Fudholi et al., 2010). Solar drying depends heavily on the prevailing environmental conditions such as wind, rainfall and cloud cover and can often bring about product contamination and cannot be applied to drying of certain products such as cardamom (Murthy, 2009).

Fudholi et al. (2010) described some of the issues associated with open sun drying as a drying technology that requires open large space, is dependent on the amount of sunlight that is available and that the dried product is susceptible to contamination during drying.

Electrical methods in which air is heated by electrical systems have also been widely used for drying different food products (Boughali et al., 2009). Fuelled systems where gaseous or liquid media is used to heat air for drying purposes have been used as well independently or in conjunction with solar drying systems (Bhattacharya et al., 2000). The reality is that these systems have low energy efficiencies among other problems such as the generation of waste heat and production of products of inferior quality due to heat damage as they depend on heat contact volumetric heating (Murthy, 2009; Fudholi et al., 2010).

With increased sense of health awareness of the global food consumers (Pereira and Vicente, 2010), there is a need to develop high quality foods which are affordable and leave a healthy ecological footprint in terms of the consumption of available natural resources and generation of minimum waste. Conventional drying systems constitute a huge chunk of industrial drying applications as described earlier in text. There is therefore an urgent need for the development and application of other drying sources such as infrared drying to dry food products and other agricultural materials so as to improve the food quality and protect the environment (Raghavan et al., 2005; Pereira and Vicente, 2010).

2.3 Infrared Drying

2.3.1 Introduction

Infrared radiation constitutes radiant energy that is part of electromagnetic spectrum and is the portion of the sun's energy that is important in heating objects on earth. Infrared radiation is generated by any object that is above the temperature of absolute zero degrees. Infrared drying utilizes this energy for drying food and other agricultural materials. Figure 2.3 depicts the electromagnetic spectrum and gives the approximate wavelength ranges for infrared radiation.

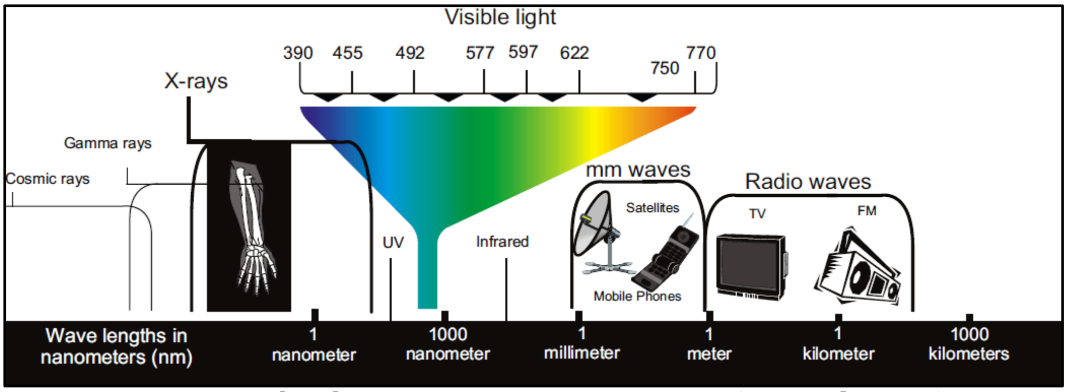

Figure 2.2 The electromagnetic wave spectrum (Jun et al., 2011)

Infrared radiation for heating and drying applications in food processing is divided into three distinct regions depending on the wavelength range of emission (Jain and Pathare, 2004; Krishnamurthy et al., 2008; Jun et al., 2011; Rastogi, 2012). These regions are the near infrared region (NIR) with a wavelength range of 0.75 to 1.4 µm, Middle infrared region (MIR) with a wavelength range of 1.4 to 3 µm and far infrared region (FIR) with wavelength ranges of 3 to 1000 µm (Sakai and Hanzawa, 1994). Infrared radiation due to its physical nature has spectral and directional dependence (Jun et al., 2011). The importance of this phenomenon is that when infrared radiation is released from different sources, it comprises of fractions of different wavelength and this influences the fate of this radiation when used for drying different food products (Jun et al., 2011).

Infrared heating has numerous applications in food processing and there are currently numerous research efforts made to understand the interaction of infrared radiation with different food materials. It is used in operations such as drying, dehydration, blanching, thawing, pasteurization, sterilization and other miscellaneous food processing operations such as roasting, frying, broiling, and cooking (Sakai and Hanzawa, 1994; Krishnamurthy et al., 2008). The use of infrared radiation in enzymatic and microbial deactivation has also been widely discussed in literature (Shi et al., 2008; Jihong et al., 2010; Vishwanathan et al., 2013).

2.3.2 Laws

There are laws that govern the propagation and absorption of infrared radiation by different materials. The wavelength in which maximum emission occurs for an infrared source is governed by the sources’ temperature (Krishnamurthy et al., 2008; Jun et al., 2011). This relationship follows the basic laws of black body radiation which include Wien’s displacement law, Planck’s law and Stefan-Boltzmann law (Krishnamurthy et al., 2008; Jun et al., 2011).

Planck's law gives the spectral characteristics of radiation emitted by a black body which emits 100% of infrared radiation at a given temperature. Infrared radiation is produced by emitter sources (point sources) which are at different individual temperatures.

Max Plank in 1901 described the spectral black body emissive power distribution for a black surface surrounded by a transparent medium of refractive index n using equation 2.7.

$$E_{b\lambda}\ T,\lambda = \frac{2\pi h C_0^{\,2}}{n^2\lambda^5\ e^{hC_0/n\lambda kT} - 1} \qquad (2.7)$$

where T the source temperature in K(t°C+273), h is Planck's constant given as 6.626 x 10^{-34} J.s, n is the refractive index of the medium, λ the wavelength in µm, C_0 is the speed of light in kms^{-1} and k is the Stefan-Boltzmann constant (1.3806 x 10^{-23} JK^{-1}).

A plot of equation 2.6 is shown in Figure 2.3.

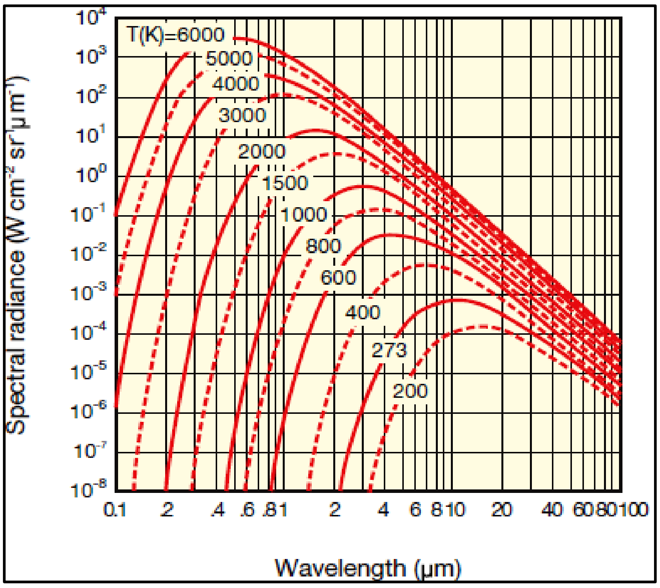

Figure 2.3 Black body emissive power spectrum (Hamatsu., 2010)

The emissive power increases with increasing temperature and the wavelengths of the corresponding maximum emissive power moves towards the shorter wavelengths. The total amount of infrared emissive power is calculated by integrating equation 2.7 for a given temperature range with respect to wavelength (Jun et al., 2011).

Wien's displacement law provides the wavelength in which the spectral distribution of radiation of a black body gives maximum emissive power and is denoted as peak wavelength. This law is as a result of differentiation of Planck's law which leads to equation 2.8 and 2.9 (Tsallis et al., 1995; Jun et al., 2011).

$$\frac{d}{d\ n\lambda T}\ \frac{E_{b\lambda}}{n^3\lambda^5} = 0 \qquad (2.8)$$

$$\lambda_{max} = \frac{2898}{T} \tag{2.9}$$

where T is the emitter temperature in K (t^oC+273) and λ_{max} is the peak wavelength.

Stefan-Boltzmann law describes the total power radiated from an infrared source at a given temperature. The amount of this radiation is described by Sakai and Hanzawa (1994) as equivalent to the integration of the Plank's law as presented by equation 2.10.

$$E_b\ T = \int_0^\infty E_{b\lambda}\ T,\lambda\ d\lambda = n^2T^4 \int_0^\infty \frac{C_1(n\lambda T)}{(n\lambda T)^5\ e^{C_2/(n\lambda T)} - 1} = n^2\sigma\ T^4 \tag{2.10}$$

where $C_1 = 2h\pi C^2_0$, $C_2 = hC_0/k$ and σ is Stefan-Boltzmann constant.

2.3.3 Mechanisms for infrared radiation absorption

The mechanisms for the absorption of infrared radiation when it impinges on food materials has been discussed by Krishnamurthy et al. (2008). They described food systems as complex mixtures of different biological polymers, salts, water and biological molecules with amino acids, peptides and proteins having strong absorption of infrared radiation at wavelengths of 3 to 4 µm and 6 to 9 µm, lipids having strong absorption of infrared radiation at the entire range of infrared band. It however has stronger absorption with three localized bands of 3 to 4 µm, 6 µm and 6 to 9 µm. Figure 2.4 illustrates the infrared absorption bands of different food elements in comparison to that of water.

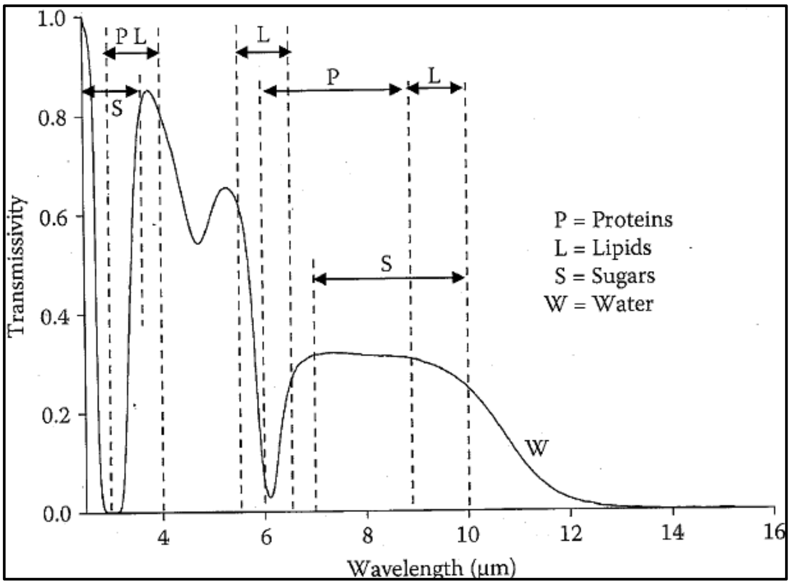

Figure 2.4 Infrared absorbtion bands for different food elements compared to that of water (Jun et al., 2011)

Decareau and Mudgett (1985) described the mechanisms for the interaction of infrared radiation with different materials. They indicated that infrared radiation causes heating up of a material through;

(a) ionization as a result of changes in electronic state of the material at wavelength ranges of 0.2 to 0.7 µm (ultra violet region),
(b) changes in the vibrational state of irradiated material which occurs at wavelengths of 2.5 to 1000 µm (FIR region), and
(c) changes in the rotational state of heated material which occurs at wavelengths greater than 1000 µm (microwaves region).

It is generally understood that efficient absorption of infrared radiation takes place at FIR bands and the subsequent heating up of biological materials occurs through changes in their vibrational state (Krishnamurthy et al., 2008).

2.3.3 Benefits of infrared drying

Infrared drying of food and other biological materials has numerous benefits that are elaborated in different sources of literature. Hamanaka et al. (2006) discussed in detail the effect of infrared heating on microbial populations. They indicated that bonding conditions of water inside bacterial spores change considerably when infrared radiation is applied on a food material affecting their development and survival. They also indicated that infrared heating target the water characteristics in a food mass and it does not alter nutritive, chemical or important quality characteristics of the food if properly applied. Pan et al. (2008) studied the infrared drying of rough rice and found out that infrared drying had high drying rates and energy efficiency when this product is dried in thin layers. Tanaka et al. (2007) and Pan et al. (2008) also indicated that infrared drying can achieve simultaneous objectives of drying and disinfecting food materials from insect infestation, microbial and enzymatic spoilage.

Yang et al. (2013) investigated the effect of sequential infrared and hot air (SIRHA) roasting on the shelf life and the quality of roasted almonds. They concluded in their study that SIRHA roasting gave roasted almonds whose quality is comparable to that of conventional hot air (HA) roasting with significantly lower production costs. Krishnamurthy et al. (2008) reviewed infrared drying of food materials and indicated some of the important attributes of infrared drying that set it apart from other drying methods. They indicated that infrared drying is characterized by high thermal efficiency and fast heating rates or response time when compared to conventional drying methods.

Afzal et al. (1999) investigated the energy requirements and quality of barley in combined far infrared and convective drying. They calculated the energy requirement for convective and far infrared drying methods. Quality attributes of germination, physical appearance and bulk density were used to assess the effects of FIR drying on barley. They concluded that FIR drying gave considerably higher drying rates compared to convective drying. Far infrared dried barley also gave high quality barley that is comparable to that of the convective drying methods with germination percentages of over 95%. The experiments also showed a general decrease in the total quality (based on the germination, physical appearance and bulk density) of barley with increasing radiation intensity at the far infrared region.

Basman and Yalcin (2011) in a study of infrared drying of noodles observed that the control, oven dried samples (control) took 22 hours to dry while infrared dried noodles took short drying durations of between 17 minutes and 3.5 minutes for emitters with lowest and highest power respectively. Infrared dried noodles also had the shortest cooking time of 3.75 minutes for the 1673 W heater compared to that of the control samples that had a cooking time of 7 minutes 30 seconds.

2.4 Modeling of Infrared Drying

Krishnamurthy et al. (2008) reviewed some of the research work carried out involving the modeling of infrared drying of different biological materials. They found out that modeling infrared drying is a research intensive area with numerous publications. There are published articles that seek explanations on the diffusion characteristics of food materials, drying thicknesses and heat transfer phenomena inside food products (Toğrul, 2005; Krishnamurthy et al., 2008; Ponkham et al., 2012). Studies to explain the radiation energy driving internal moisture migration have also been extensively covered in literature (Khir et al., 2006; Pathare and Sharma, 2006; Krishnamurthy et al., 2008; Jun et al., 2011).

Shi et al. (2008) investigated the drying characteristics of blueberries by carrying out infrared drying of both fresh and sugar infused blueberries. They used six common drying mathematical models to establish the relationship between drying time and moisture ratio (MR). The coefficient of determination (R^2), reduced chi square (χ^2) and root mean square error (RMSE) were used to evaluate the degree to which the experimental data fitted the models. These statistical values are given by equations 2.11 – 2.13.

$$R^2 = 1 - \frac{\sum_1^n \left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_1^n (MR_{exp} - MR_{pre,i})^2} \qquad (2.11)$$

$$\chi^2=\frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-1} \quad (2.12)$$

$$RMSE=\sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N}} \quad (2.13)$$

where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, $\overline{MR_{exp}}$ is the average experimental moisture ratio, N is the number of observations and n is the number of drying constants.

They concluded from their analysis that the Page model and modified Page model fitted well with the experimental data out of the six models tested.

Toğrul (2005) also modelled infrared drying behaviour of apple slices. This study involved fitting experimental data into ten empirical and semi empirical equations and they concluded that the modified Page equation was the best in explaining the drying behaviour of apple slices by establishment of the relationship between the MR and drying time.

Sharma et al. (2005b) modelled the infrared thin layer dying behaviour of onion slices. They used infrared heaters of three different intensities. The drying data was fitted into eight mathematical drying models. The Page model best fitted the experimental data and could therefore be used to explain the infrared drying behaviour of onion slices in thin layers.

Khir et al. (2011) modelled moisture diffusivity of rough rice during infrared drying. They determined the activation energies and moisture diffusivity coefficients of rough rice with a product temperature of 60°C for different bed thicknesses as $9.2 \times 10^{-9}\ m^2s^{-1}$, $6.2 \times 10^{-9}\ m^2s^{-1}$ and $4.6 \times 10^{-9}\ m^2s^{-1}$ for single layer thickness, 5mm, and 10mm, respectively, and the corresponding activation energies to be 265.2 $kJmol^{-1}$, 223.6 $kJmol^{-1}$ and 128 $kJmol^{-1}$, respectively.

Afzal and Abe (2000) modelled the moisture changes in barley during far infrared drying. The experiments were carried out at three different infrared intensities and air velocities. The modified exponential model (MEM) best fitted the experimental data and could be used to model and simulate FIR drying of barley.

Jain and Pathare (2004) modelled the convective and infrared drying characteristics of onion slices. Experiments at three levels of infrared intensities, three levels of air inlet velocities and three drying air temperatures were performed to yield 27 drying trials. The data was fitted into nine mathematical models. The results were evaluated based on goodness of fit using R^2, χ^2

and standard error (SE). A model for predicting the moisture ratio of the onion slices at different drying times was developed that had an R^2 value of 0.9995 and a χ^2 value of 4.4 x 10^{-5}.

Ponkham et al. (2012) modelled the combined FIR and hot air drying of pineapple slices with and without shrinkage. The samples were dried at air temperatures of 40-60^{o}C and infrared intensities of 1-5 kWm^{-2}. Quality models were developed using total colour difference, shear force ratio and shrinkage where these variables were fitted to empirical models. The quadratic model predicted shrinkage more accurately, while quartic model was best at estimating the colour differences and the logarithmic and modified Midilli-Kucuk model were best at estimating the shear force ratio.

Yi et al. (2010) investigated the drying kinetics of apple slices under simultaneous infrared dry blanching and dehydration with intermittent heating and then modelled the drying characteristics and the enzymatic inactivation in the product. The drying data was fitted to the empirical page model due to its simplicity and performance in accurately predicting thin layer drying of fruits and vegetables. The model is presented as equation 2.14.

$$MR = \exp(-kt^n) \quad (2.14)$$

Where MR is the moisture ratio, t is the drying time, k and n are empirical coefficients.

Equation 2.5 that describes moisture ratio for infrared drying of biological products was also used to calculate MR. The page model gave a RMSE and R^2 values of 0.013 and 0.9932, respectively and therefore could adequately represent the drying behaviour of apple slices under SIRDBD.

The effective moisture diffusivity was determined in the same study by plotting the MR against the processing time in a log scale based on equation 2.15.

$$\text{In MR} = \text{In}\ \frac{M}{M_0} = \text{In}\ \frac{8}{\pi^2} - \pi^2 \frac{D_{eff}t}{H^2} \quad (2.15)$$

where H is the slice thickness t is the drying time and D_{eff} is the effective moisture diffusivity.

The activation energy of the drying process was determined from the slope of the curve where the effective moisture diffusivities were plotted against absolute surface temperatures, based on equation 2.16.

$$D_{eff} = D_0 \exp\ -\frac{E_a}{RT_s} \quad (2.16)$$

where D_0 is the reaction coefficient, E_a the activation energy, R is universal gas constant and T_s the absolute target surface temperature (t^{o}C+273) K.

2.5 Infrared Drying and Product Quality

The quality of dried food and agricultural materials often influence customer acceptability and is dependent on the product in question. Studies on the effects of infrared drying on different products have been carried out and discussed in literature. Basman and Yalcin (2011) studied the quality changes during infrared drying of noodles. They observed that infrared drying of noodles caused rapid moisture loss which then results in the development of bubbles in the product interior giving the final product distorted shapes. They used docking in their investigation to manage this problem. Docking is a process done in preparation of products for baking by making small holes on the unbaked product to allow air/steam to escape hence prevent the baked product from rising or blistering (Dodgshun et al., 2011). The infrared dried noodles gave a significantly lower cooking loss compared to the control (oven dried for 22 hours at 45^oC). Cooking loss is the total amount of solid substance lost to the cooking water after an optimal cooking time. Higher infrared intensities gave lower cooking losses. This was attributed to the partial coagulation of gluten structure in the product. Infrared dried noodles however gave a significantly lower total organic matter (TOM) content and lower swelling volumes indicating their inferior quality. It was concluded that the 1673 W emitter gave better quality with lowest cooking loss and TOM values compared to the other heaters ranging from 273W to 1782 W. Both infrared and conventional drying did not cause gelatinization of starch granules in the food complex of the noodle samples. The study also showed that infrared drying of noodles reduced the relative intensities of protein types with molecular weights of between 66000 and 97000 and significant increases in the amount of dietary fiber.

Yi et al. (2010) investigated the quality characteristics of apple slices under simultaneous infrared dry blanching and dehydration (SIRDBD) with intermittent heating. The study investigated three processing parameters that relate to the product quality. These are product surface temperature, slice thickness and processing time. They conducted a three factor experimental design to investigate the effects of these parameters on the drying characteristics of apple slices and the final quality (indicated by slice surface colour, moisture reduction, peroxidase (POD) and poly phenol oxidase (PPO) activities). They established that thin apple slices heated up faster than thicker ones and thicker slices had a higher average centre temperature. Thin slices also gave lower PPO activities with slice thickness having a higher impact on inactivation of PPO than change in temperature. POD showed similar inactivation characteristics to that of PPO. Colour changes of the product during the study were also observed and reported using the L*a*b method. It was concluded that an apple temperature of 75^oC was the best temperature that gave a reasonable processing time and the least total colour difference (ΔE) of 2.27 under SIRDBD.

Vishwanathan et al. (2013) investigated the effects of infrared blanching and infrared assisted hot air drying on the quality of carrot slices. The processing quality characteristics of their system were compared to those of conventional blanching and drying methods. Enzyme inactivation level, retention of vitamin C and rehydration characteristics of the products were used to indicate product quality. The effect of sample thickness on inactivation of POD was also investigated. Thinner slices (5mm) were blanched faster than thicker (10mm) slices which took 10 minutes and 15 minutes, respectively. Retention of vitamin C was investigated and the study showed that the retention of vitamin C by infrared blanched samples was significantly higher than that of conventional methods. The study also showed that infrared blanching took longer compared to the conventional blanching methods but it was recommended due to its higher nutrient retention.

The study also investigated the rehydration characteristics of infrared blanched carrot slices as an indication of the structural quality. It was observed that the rehydration of infrared blanched samples was approximately 5% higher than the rehydration capacity of conventionally blanched and dried samples. This was attributed to the uniform heating of infrared drying technology and the resultant absence of case hardening.

Jihong et al. (2010) investigated some of the quality changes during infrared drying and pasteurization of almonds. Sensory attributes were tested by a panel of 90 untrained panellists. SIRHA roasted and HA roasted almonds were tested in terms of their texture, flavour, appearance and overall quality. Colour changes after the two treatments were also measured. Recommendations for the medium roast based on the industry standards were given for infrared roasted almonds in terms of the infrared intensity, roasting time and temperature based on the colour changes. The sensory quality for both infrared roasted almonds and HA roasted almonds showed no significant difference based on a two way ANOVA data analysis.

2.6 Methods of Quality Analysis

Drying of food products affects their quality, and drying methods that minimize quality changes in food processing should be developed and adopted. There are numerous quality parameters that can be used as indicators of quality for different products and have been discussed in literature as well as the methods of their analysis documented as standards. The important quality parameters considered during a drying process will depend on the nature of the product being dried and its end use. Some of the important quality indicators include nutrient changes, colour changes, product rehydration and textural characteristics of the end product.

2.6.1 Colour

Colour of food products is considered an important quality parameter that is influenced by the chemical, microbial, biochemical and physical state of a product after its production, postharvest handling and processing. Colour in itself is an indirect method for the measurement of food's quality. The methods of food colour measurement comprise instrumental (objective) and visual (subjective) methods (Pathare et al., 2013).

Pathare et al. (2013) and MacDougall (2002) described colour as an attribute measured with reference to several coordinate systems. Some of the most popular colour coordinate systems are given as,

(a) RGB (Red, Blue, Green commonly used in colour video monitors)
(b) Hunter L a b
(c) CIE L*a*b
(d) CIE XYZ
(e) CIE L*u*V
(f) CIE Yxy
(g) CIE LCH

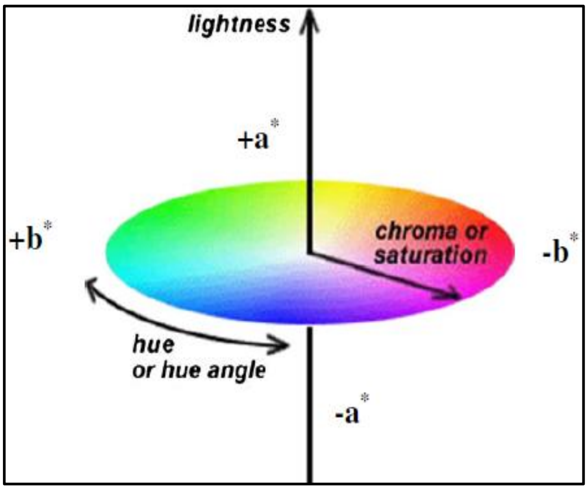

Figure 2.5 The CIE L*a*b coordinate system (Pathare et al., 2013)

They indicated that colour quantification is commonly given based on the HunterLab L*, a*, b* and CIELAB scales. These two scales are widely used in the food processing industry (Carpenter et al., 2001; MacDougall, 2002; Pathare et al., 2013). In the CIELAB colour space, a* and b* are the colour coordinates and L* a psychrometric index of lightness and they are all read directly from their respective colour spaces. The parameter a* takes positive values for reddish colours and negative values for greenish colours while the parameter b* takes positive values for yellowish colours and negative values for bluish colours. The L* value estimates the luminosity or the lightness with values ranging from 0 to 100 (MacDougall, 2002)

Chroma (C*) is described as the quantitative measurement of colourfulness given by the equation 2.17. The higher the chroma values the higher the colour intensity as perceived by the human eye.

$$C^* = \sqrt{a^{*2}+b^{*2}} \quad (2.17)$$

The hue angle (h*) is given by equation 2.18 and higher hue values represent less yellowness, hue angles of 0^o or 360^o = Red hue, 90^o = Yellow hue, 180^o = Green hue and 270^o = Blue hue.

$$h^* = \tan^{-1}\frac{b^*}{a^*} \quad (2.18)$$

The total colour difference (ΔE) indicates the quantitative changes during a processing step and may be used to show product quality changes. It is presented in form of equation 2.19.

$$\Delta E = \sqrt{\Delta a^{*2}+\Delta b^{*2}+\Delta L^{*2}} \quad (2.19)$$

The whiteness index (WI) gives the overall whiteness of food materials and can show the level of discolouration during a drying process which is important in predicting heat damage. It is presented by equation 2.20.

$$WI = \sqrt{(100 - L^*)^2 + a^{*2}+b^{*2}} \quad (2.20)$$

Colorimeters are the basic instruments used for the measurement of colour of food materials in the food processing industry. The other instrument system used is the computer vision measurement system. Product images are captured for these systems using either a charge coupled device (CCD) camera, ultrasound, magnetic resonance imaging (MRI) or computed tomography (CT). Subsequent steps taken after image acquisition consist of image pre-processing, image processing and subsequent analysis based on industry colour space models. Hue intensity saturation schemes (HIS) system commonly gives good results in this respect (Pathare et al., 2013)

2.6.2 Textural characteristics

Textural properties of food are important quality attributes which indicate their level of maturity and their ability to meet handling, packaging and processing requirements. Chen and Opara (2013) described food texture as “all the rheological and structural (geometric and surface) attributes of a product perceptible by means of mechanical, tactile and where appropriate visual and auditory receptors". They described the textural properties of foods as measurable by means of descriptive sensory (subjective) and instrumental (objective) analysis. Subjective methods constitute mainly the use of a sensory test panel that evaluates the textural properties of food materials. The number of people that make up sensory panels as well as the methodologies adopted may vary and the panel may be trained or untrained. Sensory panels often use a sensory scale and have numerous limitations that instrumental methods are designed to eliminate. Instrumental methods are classified into destructive and non-destructive methods. Some of the destructive methods include three point bending test, single-edge notched bend (SENB) test, compression, puncture test, and imitative methods (Bourne, 2002; Chen and Opara, 2013). Some of the non-destructive methods include ultrasonic methods, mechanical methods and optical techniques with a wide range of instruments being used for both destructive and non-destructive methods (Bourne, 2002).

2.6.3 Rehydration characteristics

Rehydration of dried food materials measures the level of structural changes that occur in food matrix after a processing step or a combination of these. Lewicki (1998) described rehydration as a measure of the magnitude of injuries inflicted on food products during a drying process and other handling operations prior to rehydration. Rehydration tests can be carried out using different procedures of measurement as well as rehydration times ranging from 2 minutes to 24 hours. Different formulas for the measurement of rehydration are presented and three are shown in equation 2.21 - 2.23 (Lewicki, 1998; Maskan, 2001).

$$\text{Rehydration ratio} = \frac{\text{Weight after rehydration}}{\text{Mass of dry matter}} \tag{2.21}$$

$$\text{Rehydration capacity} = \frac{\text{Weight of water absorbed during rehydration}}{\text{Weight of dry matter}} \tag{2.22}$$

$$\text{Coefficient of rehydration} \quad CR = \frac{M_2(100 - W_f)}{M_1 - 0.01 \cdot M_1 \cdot W_0} \tag{2.23}$$

where M_1 is the weight of the dry material in grams, M_2 the weight of the rehydrated material in grams, W_0 the moisture content after drying (% d.b) and W_f is the final moisture in the dry material (% d.b).

Maskan (2001) investigated the rehydration, shrinkage and drying characteristics of Kiwi fruits under different drying methods. They compared the rehydration characteristics of kiwi fruits dried under microwave, conventional HA method and combined microwave and HA systems. Rehydration of the samples was done after the completion of the drying processes where the samples were weighed and immersed in hot water at 50^{o}C for 50 minutes. The samples were reweighed after every 10 minutes by removing them quickly from the water for no more than 30 seconds. The rehydration capacity, also described as percentage of water gain, is mathematically presented in equation 2.24.

$$\text{Weight gain } \% = \frac{W_t - W_d}{W_d} \, 100 \quad (2.24)$$

where W_t is the rehydrated weight at time t and W_d the initial weight after drying.

It was noted that samples that had fast rehydration capacity had good quality. Combined microwave and HA dried samples gave higher rehydration capacities and low shrinkages compared to the other drying methods thus indicating better quality.

2.6.4 Shrinkage

Shrinkage constitutes a reduction in size after food materials undergo different processing steps. Food materials commonly shrink after drying indicating physical and chemical change within its structure. Mayor and Sereno (2004) reviewed the effects of drying on the shrinkage properties of food products. They indicated that cracking of dried products is as a result of non-uniform shrinkage and cracking reduces the rehydration capacity of food materials. Shrinkage is "relative or reduced dimensional change of volume, area or thickness". Bulk shrinkage can be presented in form of equation 2.25 (Mayor and Sereno, 2004).

$$S_b = \frac{V}{V_0} \quad (2.25)$$

Where S_b is the bulk shrinkage, V is the final volume and V_0 the initial volume of the product. S_b values range from 0 to 1.

The study detailed the mechanisms of shrinkage as well as different models used to predict shrinkage of different food materials during a drying operation.

Bacelos and Almeida (2011) studied the shrinkage of blanched and dried spherical potato samples of 10 mm radius. They recorded the weight and size changes during drying using a weighing and computer vision system. The shrinkage results were fitted into shrinkage models. Both the linear model and Kilpaltrick models gave a good account of the shrinkage process.

Yan et al.(2008) investigated different methods used for the measurement of shrinkage of banana, mango and pineapple after drying. Four methods were proposed and used to conduct shrinkage experiments for these products after drying. The true shrinkage values were thereafter measured using a gas pycnometer. The Archimedes principle method using n-heptane gave a lower coefficient of variation indicating better accuracy compared to the solvent displacement, glass beads displacement and liquid pycnometry methods.

2.7 Infrared Drying and food safety

The presence of contaminants in food materials of different nature and origins greatly affects their food safety. Of important consequence is the occurrence of high microbial levels and spoilage causing enzymes during food handling and processing operations. Infrared drying is able to achieve both drying and inactivation of microbial elements as well as elimination of enzymatic spoilage (Tanaka et al., 2007; Vishwanathan et al., 2013).

Tanaka et al. (2007) investigated the FIR heating as an alternative decontamination method of strawberries using FIR heaters of different power intensities and configurations. It was recommended that heating be from four orthogonal directions towards the food sample in order to achieve higher decontamination levels, uniform heating and less damage to the strawberries. It was also concluded that further investigations on the cyclic heating should be done in order to assess further possibilities of FIR decontamination of strawberries.

Hamanaka et al. (2006) investigated the effect of infrared emitter wavelength on decontamination of bacterial spores. In their study, they concluded that the inactivation of these spores is dependent upon the water activity level of the product and the peak wavelength of the emitter. This implied that an optimum emitter spectrum has to be selected for a given water activity level.

Nortjé et al. (2005) studied the effect of gamma irradiation on the sensory quality of biltong and observed that conventionally dried biltong did not achieve the recommended food safety requirement of 5.0 log reduction of microbial populations (USDA, 2012). The use of gamma irradiation at a level of 4 kGy to 8 kGy achieved this requirement without adversely affecting the sensory quality of biltong. They therefore recommended a gamma irradiation dose of no more than 4 kGy since it resulted in the best sensory quality scores. Infrared heating from the foregoing discussion, can be used achieve microbial reduction in biltong and guarantee its food safety.

2.8 Biltong

Infrared drying as discussed in preceding chapters can confer a host of benefits to ready to eat (RTE) meat products such as biltong, a product that will be the subject of study in this research.

Biltong is a meat based snack widely consumed in South Africa and is commonly described in the country as a national delicacy. There are different recipes for the preparation of biltong some of which are custom designed depending on the individual consumer preferences. Lewis et al. (1957) described the origin of the word 'biltong' and its preparation. They indicated that the word biltong is made up of two parts, '*bil*' referring to the hindquarters of an animal and '*tong*' which means a fillet. It is a product that has been in existence for centuries in South Africa and has been commonly used by nomads and trekkers. A similar product also exists in Switzerland, Norway and North American Arctic known as Pemmican. Biltong is also consumed to a limited extend in the southern Africa region (FAO, 2013). Biltong is generally prepared from meat products from freshly killed herbivores by cutting the loin region lengthwise in lengths varying from 1 to 2 feet and strips 2 inches wide (Lewis et al., 1957; Nortjé et al., 2005). The strips are then salted using coarse salt (1-2 kg for every 50kg of meat) and spiced with ingredients such as pepper, garlic, sugar, coriander or aniseed to meet the taste preferences of consumers (FAO, 2013). They are then dried by hanging outside in ambient air under a shade to protect it from rain, frost or dew. The dried biltong is then ready for storage or consumption after 10-14 days.

Nortjé et al. (2005) prepared biltong for their experiments from 300-350 g beef strips purchased from a commercial biltong producer, Gill foods. They salted and marinated the strips for 12 hours in a sodium chloride based solution and hung them for 48 hours in air with temperatures of 28-32^{o}C and relative humidity of 70%. In the study, the chemical composition of moist beef biltong is presented as shown in table 2.3.

Table 2.3 Chemical and intrinsic properties of moist beef biltong (after Nortjé et al., 2005)

Parameter	Mean value (±standard deviation)
Moisture content (%)	46.7 (±1.27)
Protein content (% w.b)	45.2 (±1.19)
Crude fat content (% w.b)	1.53 (±0.09)
Ash content (% w.b)	5.65 (±0.17)
NaCl content (% w.b)	3.70 (±0.18)
NaCl in moisture content (%)	7.94 (±0.67)
a_w	0.919 (±0.008)
PH	5.53 (±0.05)

2.9 Discussion and Conclusion

Infrared drying technology is an immensely active research area as a drying method with numerous benefits when successfully applied to drying of different food products. However, published articles to date reveals gaps and challenges which call for further research.

Biltong is particularly a product that can benefit from infrared drying from a food safety and quality stand point. There are currently no published articles on infrared drying of biltong. The effects of different spicing methods, drying methods as well as product sizes on quality attributes of biltong have not been investigated. These factors are important in designing processes that optimize the production of high quality products.

The effects of drying parameters particularly the air velocity and relative humidity should be investigated during infrared drying in order to establish the point where these parameters give the highest energy efficiency. Infrared drying models for biltong have also, currently not been investigated and developed. There is also the need to study the storage stability of dry biltong in order to establish the critical parameters that can significantly extend its shelf life. The section on the proposal that is contained in the next few pages is therefore geared towards meeting some of the research gaps highlighted above.

3. PROJECT PROPOSAL

3.1 Introduction

Drying as a food processing and preservation method gives numerous benefits to food producers and consumers. These benefits should be balanced or optimized through the understanding of the intricacies of the drying process of a given product (Mwithiga, 2007).

Currently, investigations on the drying characteristics of biltong have not been carried out with any published articles available on the application of infrared radiation to dry biltong.

Infrared drying as discussed in the previous chapters produces products of better quality compared to conventionally dried products and maximizes on energy savings. Infrared dried biltong in the same vein will confer these benefits and ensure that premium products with desirable nutritional, sensory and textural attributes can be produced through fast and cost-effective processes. The successful application of infrared radiation to dry biltong requires the understanding of the product's drying characteristics under different drying conditions.

This study therefore seeks to investigate the drying kinetics of biltong under different pre-treatment and drying conditions, and the effect of these on the resultant product quality.

The specific research objectives are:

(a) To investigate the effects of varying product thickness, spicing level and drying method on the dying kinetics of biltong.

(b) To establish the performance of two infrared heaters with different emission characteristics in terms of product quality and efficiency.

(c) To study the goodness of fit of drying data into well-established drying models.

3.2 Research Questions

Data will be collected so as to answer the following research questions:

(a) Does the product thickness influence its drying characteristics?

(b) What model best explains infrared drying of biltong?

(c) How does the spicing level influence the drying characteristics of the product?

(d) Does the spicing level influence the quality of the product after drying?

(e) Which drying method, thickness, product spicing level has no significant differences with the whiteness index (WI) of the control sample?

(f) Which infrared heater gives good sensory and other good quality attributes and how does this compare with the control?

3.3 Experimental Set-up

3.3.1 Infrared drying rig

The drying rig will consist of a rigid angle bar frame with a stainless steel plate welded at its lower end to support the drying samples and apparatus. Its four sides are completely open to allow for free moisture movement from the products to the surrounding ambient air. The drying plenum will consist of an assembly of food grade wire grill where the products will be placed during drying. Underneath this, will be a water collection pan that will collect any dripping moisture from the drying products to avoid damage to the electronic balance that will measure the samples weight changes as drying progresses.

The rig will accommodate infrared heaters with intensities of up to 15500 W.m^{-2} whose height will be adjusted from the drying plenum to give intensities of 1000-5000 W.m^{-2} measured using an infrared power meter (Linshang, China). The final intensity for the drying runs will be selected based on preliminary drying runs. The heater mounting platform on top of the rig will be the rail type that will allow for easy mounting and removal of different heaters. Utmost care will be taken to ensure that the heaters are mounted level to avoid non-uniform heating. The heaters will have the same intensities but different emission wavelengths.

The heaters will be adjusted level to a maximum height of 400 mm from the drying plenum. The drying area of the rig will be 300 mm by 300 mm sized according to size of sample required for all the tests per drying run. Experimental investigations for purposes of this research will assume a zero air movement (velocity) around the drying products.

Figure 3.1 illustrates the assembly of the drying rig.

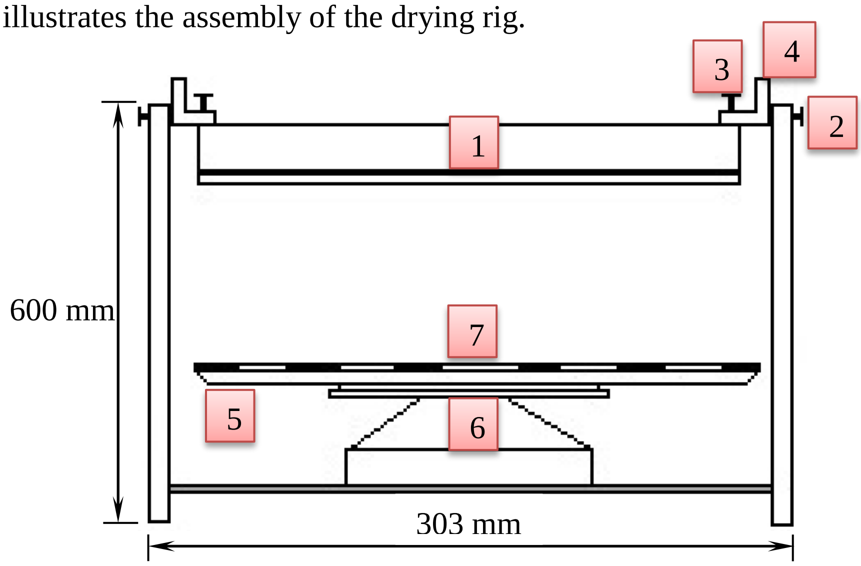

Figure 3.1 The side view of the infrared drying rig. Parts 1-7 are: 1- infrared heater assembly, 2-height adjustment screw, 3-locknut for mounting, 4- mounting rail, 5-drain pan, 6-electric balance and 7-drying plenum made of food grade wire

3.3.2 Instrumentation

The temperature of biltong will be measured using K type thermocouples (accuracy ± 1.2^{o}C) and the data will be imported directly to computer memory using OM-DAQ-USB-2401 data logger (Omega, UK). Weight changes during drying will be recorded manually at suitable time intervals based on preliminary investigations using a digital balance (Model CQT 202, Adam Core, UK).

The textural properties of dried biltong will be assessed using a textural analyser (model 3345, Instron, USA) with two testing probes; a knife edge probe and a serrated probe to mimic mastication. These will show the level of tenderness in the product interior as well as the surface hardness. Colour changes will be assessed using a ColourFlex colorimeter (Model EZ 45/0, Hunterlab, USA). Values of L*, a* and b* will be manually recorded for each sample tested. The readings of these colour values will be done before and after drying. Drying runs for the control will be done to mimic the ambient conditions. Based on the method suggested by Nortjé et al. (2005), this will be carried out at 25^{o}C and 60% relative humidity for 4-6 days per drying run in the climate control chamber(Model C-40/100, Controltechnica, Germany). Drying will end when the products reach a moisture content of 11% d.b (Lewis et al., 1957; Rao, 1997).

3.4 Preparation of Biltong

Beef samples for the drying tests will be prepared based on the guidelines given in literature (Lewis et al., 1957; Nortjé et al., 2005; Nortjé et al., 2006). The samples will be made of strips 25mm wide, 150mm long and three different thicknesses, 5mm, 10mm and 15mm. They will be sourced and trimmed to size at local butcheries near Pietermaritzburg, South Africa. The samples will be cut from a slaughtered beef carcass and used for experiments the same day. Due to surface moisture loss that occurs in beef carcasses, the samples will be prepared from slices cut 1-2 cm from the carcass surface in order to obtain samples with high initial moisture content (Trujillo et al., 2003). Slicing to the required sizes will be done immediately after cutting from the carcass. This will be done along the muscle fibres to minimize rapturing them (Trujillo et al., 2003). The fat tissues should be kept at a minimum through careful selection of the part to be cut. The hind limbs will be a good spot that will meet this requirement. Upon slicing, they will be packed in polyethylene bags and transported to the laboratory within an hour where the initial moisture content of fresh beef will be determined using the AOAC 950.46 standard method suggested by Nortjé et al. (2006). The samples will then be stored at a temperature of 4^{o}C before pre-treatment processes commence. Samples of different thicknesses will be marinated at three levels. Dzimba et al. (2007) recommended marination of biltong to be done for a maximum of 18-24 hours.

Three 2 litre beakers will be used to marinate the samples for the required period of time. The marinade in each of the containers will be equal in concentration in order to ensure that samples receive the same treatment. In addition, the number and sizes of the samples in each marinade will be equal. Marinating will be done at the storage temperature of 4^{o}C.

Drying will commence when marination of samples reaches completion. Excess moisture from the product surface will be removed using serviettes and the colour of the marinated product will then be measured using a colorimeter.

3.5 Drying of Biltong

Experimental runs will begin after the measurement of the colour of marinated samples. The infrared intensity of the two infrared heaters will be set at the same level. Similarly, the control samples will be dried in the climate control chamber set at a RH and temperature of 60% and 25^{o}C respectively and allowed to stabilize. The marinated samples will then be removed from the storage chamber and samples placed on each of the drying plenum of the infrared heaters per drying run. Weight changes will be recorded at specified time intervals based on preliminary experimentation. Thirty one samples will be dried per drying run for the control samples, where the moisture content will be determined at suitable intervals. The equilibrium moisture content of biltong will be determined by placing raw beef in the climate control chamber at set conditions (60% RH and 25^{o}C) until it attains a constant weight.

The drying runs will comprise of 27 drying experiments where the factors will be the drying system (control and two infrared heaters with surface temperatures of 870^{o}C and 980^{o}C), the product thickness (5mm, 10mm and 15mm) and three marinating levels (6 hours, 12 hours and 24 hours). Each factor is replicated three times (Abe and Afzal, 1997).

The experimental design will be a randomized complete block design (RCBD) with three treatments (3 drying systems, 3slice thicknesses and 3 spice levels) replicated three times yielding a total of a total of eighty one drying runs.

3.6 Infrared model for Drying of Biltong

There are numerous drying models that can be used to predict the drying behaviour of different food and agricultural materials. From the widely used models in infrared drying of food materials, the following drying models will be used for this study:

(a) Page model

(b) Modified page model
(c) Henderson and Pabis model
(d) Newton model
(e) Diffusion model

The modeling process will be based on the methodology that was used by Toğrul (2005). These models were chosen due to their simplicity, their wide applicability and performance in describing IR drying for a wide range of food products (Wang, 2002; Sharma et al., 2005a; Toğrul, 2005; Toğrul, 2006; Ruiz Celma et al., 2008). The performance of these models in describing the drying characteristics of biltong will be on the basis of the RMSE and R^2 values given by equation 2.11 and 2.13 in regression analysis.

3.7 Product Quality

After drying, the colour changes of the dried product will be assessed using a colorimeter as described in section 3.3.1. Three samples of sizes 250 by 150mm will be drawn at random for this purpose per drying run. The data collected from the replications will be averaged for each drying run. Textural changes after drying are important attributes that indicate the quality of the dried product. Destructive mechanical tests will be carried out based on the method given in section 3.3.1 and conclusions made as per the collected data. The force required to penetrate the sample and the depth of penetration of indenters will be the subject of measurement by the textural analyser (Chen et al., 1979; Bourne, 2002). Two indenters will be used; one will measure the surface hardness and the other to assess the tenderness in the product interior. Product shrinkage will be measured by the Archimedes principle using n-heptane as the displacement liquid. The method is described in detail by Yan et al. (2008) as well as Sjöholm and Gekas (1995) and will be used in this study due to the low coefficient of variation against true values in the study by Yan et al. (2008). Rehydration capacity will be measured using the methodology described by Lewicki (1998). A test panel of 12 untrained people will be used to assess the sensory attributes of the dried biltong. The panel will give each sample a score on a 6 point numerical (6 for very large difference and 0 for no difference) scale (Kemp et al., 2009) for taste and softness (Cross et al., 1978). In this case, a difference from control test will be carried out based on the method suggested by (Kemp et al., 2009)

3.8 Data Analysis

Data collected from these experiments will be analysed to yield the drying kinetics of biltong under ambient conditions and infrared drying conditions. Regression analysis will be carried out using GENSTAT on the moisture content data to establish the model coefficients as well as the R^2 and RMSE values. This will be used to assess the suitability of the models in predicting the drying process of biltong. Drying curves will also be developed for each drying run as well as three dimensional plots of product temperature to assess the heating uniformity across the drying plenum (Nowak and Lewicki, 2004).

Analysis of variance (ANOVA) will be carried out on the quality assessment data to in order to answer the formulated research questions.

Mean separation will be carried out using the least significant difference (LSD) method at a $P \leq 0.05$ significance level.

3.9 Resource Requirements

This project will require laboratory space, laboratory equipment, office space, stationary, internet access, computer and consumables. The appendix section details the equipment and material requirements for this research.

The funds for these resources are available through the University's research grant.

3.10 Work Plan

	2013												2014											
ACTIVITIES	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Reading and collecting literature	■	■																						
Writing literature review		■	■	■																				
Preparation of proposal		■	■	■	■																			
Corrections		■	■	■	■	■																		
Preparation and presentation of proposal						■																		
Sourcing of infrared lamps			■	■	■	■	■	■																
Sourcing of measuring equipment				■	■	■	■	■	■															
Sourcing drying rig fabrication materials					■	■	■	■	■	■														
Fabrication and assembly of drying rig											■	■												
Instrument set up and testing												■												
Sourcing of beef for biltong preparation													■											
Preparation of beef samples													■											
Preliminary experimental runs													■											
Experimentation and data collection														■	■									
Results reporting in thesis																■								
Data analysis and presentation																■	■	■						
Discussion of results																		■	■	■				
Conclusion/recommendations																					■			
Final thesis preparation																						■	■	
Corrections																							■	
Submission																							■	■

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5. APPENDIX

5.1 Equipment Required

Equipment	Model	Manufacturer/Company	Country	Availability
Infrared dryer	Assembled	Assembled	Various	Procured
Climate control chamber	C-40/100	Controltechnica	Germany	From July 20, 2013
Moisture oven	9245	Prolab	Germany	Available
Texture analyzer	3345	Instron	USA	Available
Meat mincer	Local	Local	South Africa	Procured
Colorimeter	EZ 45/0	HunterLab	USA	Available
Electric balance	CQT 202	Adam core	UK	Available
Infrared power meter	LS127	Linshang	China	Procured
Kwh Meter	DEM015SG	Acorp	South Africa	Procured
Data logger	OM-DAQ-USB-2401	Omega	UK	Procured
Infrared thermom-eter	ST667	ASSTech	South Africa	Procured

5.2 Materials Required

Material	Source	Quantity required
Sliced beef	PNP	40Kg
2 Litre beaker	Local	6 Pieces
Blotting papers/Serviettes	PNP	4 Packets
Knife	PNP	1Piece
Moisture pans	Local	20 Pieces
Spice	South African biltong makers	5 Kg
Sample bags	Local	100 Pieces
Lab coat	Local	1 Piece
Pans	Local	10 Pieces
Wire grill	Available	2 Pieces
N-Heptane	Laboratory and Analyti-cal Suppliers	5 Litres
K-type thermocouple wire	Omega	25 Feet