COMBINED INFRARED HEATING AND HOT AIR DRYING OF BEEF FOR BILTONG PRODUCTION

FC Muga

Submitted in partial fulfilment of the requirements

for the degree of PhD

School of Engineering

University of KwaZulu-Natal

Pietermaritzburg

2019

Supervisors: Professor TS Workneh

Dr MO Marenya

ABSTRACT

The popularity of biltong as a ready-to-eat meat-based snack, continues to expand within South Africa and globally. Consumer demands for consistency in quality and safety, especially for European markets, is a major hindrance to the full exploitation of the increasing market opportunities. Literature reviewed indicate that the current methods of processing meat into biltong are incapable of ensuring its microbial safety. Hence, the need to explore other technologies that can maintain the nutritive quality of biltong and ensure its microbiological safety. Infrared heating is an alternative drying method that produces dried products of better quality, significantly reduces the risk of pathogenic bacteria and toxigenic fungi, and impacts positively on the energetic, exergetic, and heating efficiency. Using a combination of infrared heating and hot air to dry agricultural products, offers significant advantages compared to using either of the methods independently. Thus, a combined infrared heating and hot air drying could be a viable alternative to hot air drying for processing meat into biltong. The application of new drying methods to dry agricultural products, requires a scientific understanding of the drying process. Thin layer drying models have been used extensively to describe the drying kinetics of agricultural products. However, these models are incapable of providing information on the heat and mass transfer within the product. Coupled heat and mass transfer models account for the various mechanisms involved in the drying processes. Developing a coupled heat and mass transfer model for the drying of meat using a combination of infrared heating and hot air will enhance the understanding of the underlying mechanisms involved during biltong production. The model could give insight into the interaction between the drying process variables and their influence on the drying kinetics of meat and corresponding quality attributes of the resulting biltong. The proposed model will ascertain the suitability of a combined infrared and hot air drying for biltong production. This proposal seeks to develop a mechanistic model of the heat and mass transfer in meat, establish the drying kinetics of meat, and evaluate the quality attributes of the biltong produced using a combined infrared heating and hot air drying approach.

PREFACE

I, Muga FC, declare that:

(i) The literature review and proposal reported in this document, except where otherwise indicated, is my original work.

(ii) This literature review and proposal has not been submitted for any degree or examination at any other university.

(iii) This literature review and proposal does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

(iv) This literature review and proposal does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then;

a) Their words have been re-written, but the general information attributed to them has been referenced.

b) Where their exact words have been used, their writing has been placed inside quotation marks, and referenced

(v) Where I have reproduced a publication of which I am an author, co-author or editor, I have indicated in detail which part of the publication was actually written by myself alone and have fully referenced such publications.

(vi) This literature review and proposal does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and the references section.

Signed: Date

…………………….. ……………………

Francis Collins Muga

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Biltong is a dried meat product that is predominantly consumed in South Africa. It is widely made from beef and game meat (kudu, springbok and gemsbok), chicken or ostrich (Dzimba *et al.*, 2007; Naidoo and Lindsay, 2010a; Strydom and Zondagh, 2014; Jones *et al.*, 2017). Traditionally biltong is sun dried (Strydom and Zondagh, 2014). However, the rising popularity of biltong has spurred the development of a variety of biltong dryers. The available dryers range from simple domestic types to high capacity commercial dryers. The market for biltong has expanded both locally and internationally (Attwell, 2003), prompting its increased production. The market value of biltong in South Africa was estimated at US$ 170 million in 2015 (Jones *et al.*, 2017). The expansion and acquisition of new markets for biltong is hampered by food its safety concerns and inconsistent quality characteristics (Attwell, 2003; Burfoot *et al.*, 2010).

A variety of recipes and drying methods used by biltong producers result in a wide range of physico-chemical properties *viz*. moisture content, salt content, water activity, and pH (Van der Riet, 1976; Osterhoff and Leistner, 1984; Attwell, 2003; Nortjé *et al.*, 2005; Petit *et al.*, 2014; Strydom and Zondagh, 2014). In addition, biltong production methods are not entirely inhibitory to microbial contamination (Wolter *et al.*, 2000; Burfoot *et al.*, 2010; Mhlambi *et al.*, 2010; Naidoo and Lindsay, 2010a; Naidoo and Lindsay, 2010b; Allotey *et al.*, 2014). The conventional hot air drying (HAD) method used in commercial production of biltong, does not achieve the recommended microbial levels in the resultant biltong (Nortjé *et al.*, 2005). Furthermore, HAD is a slow and energy intensive drying method that significantly degrades the physical quality of dried biltong (Ratti, 2001; Sharma and Prasad, 2001; Kowalski and Mierzwa, 2009). Case hardening (Bellagha *et al.*, 2007) and shrinkage (Duan *et al.*, 2011), are of particular concern to biltong producers. These concerns underscore the need for alternative drying methods that would preserve the quality and ensure the microbial safety of biltong in a cost-effective way.

Novel heating technologies like microwave, inductive heating, radio frequency, and infrared provide volumetric heating that positively impacts on the energetic, exergetic, and heating efficiency (Rastogi, 2012). According to Li *et al.* (2018), infrared (IR) radiation can improve the dehydration efficiency of beef jerky (a dried meat product popular in the Americas). Similarly, Cherono *et al.* (2016) reported improved drying rates during IR drying of biltong. Moreover, the

IR dried biltong exhibited lower microbial loads than the hot air dried biltong (Cherono *et al.*, 2016). A combined IR and HAD (IRHAD) consumes less energy and produces dried products of higher quality compared to using IR or HAD independently (Afzal *et al.*, 1999; Hebbar *et al.*, 2004). Therefore, IRHAD is a possible alternative to HAD of meat during the process of making biltong.

Understanding the dehydration process is key to the development of new efficient drying methods (Defraeye, 2014). Modelling and simulations tools are useful in decoding the mechanism of the drying processes and predicting the drying behaviour of products (Onwude *et al.*, 2018). However, the drying kinetics of meat during biltong processing, have not been sufficiently characterised (Jones *et al.*, 2017). The diffusion approximation model recommended by Cherono *et al.* (2016) is a theoretical model based on Fick's second law of diffusion (Ertekin and Firat, 2017). Thus, the model is not able to predict the temporal and spatial changes in temperature and moisture in meat during biltong processing. There is no documented study on modelling the heat and mass transfer in meat during the process of making biltong. Consequently, it is necessary to effect a study on the drying of meat that would enable the prediction of the drying behaviour of meat when subjected to new biltong processing methods such as IRHAD.

2. REVIEW ON BILTONG AND MODELLING OF THE HEAT AND MASS TRANSFER IN MEAT DURING BILTONG PROCESSING

2.1 Background

Biltong is a dried, spiced meat-based ready-to-eat snack that is widely consumed in South Africa (Cherono *et al.*, 2016). It can be compared to other dried meat products across the world such as; carne seca, charqui, jerky, kilshi, and rou gan from Mexico, South America, USA, Sahel, and China, respectively (Dzimba *et al.*, 2007; Mhlambi *et al.*, 2010; Petit *et al.*, 2014). Salt is the main curing agent. The salt, together with other spices contained in the marinating mixture, give biltong its distinctive flavour. Traditionally, biltong is dried under ambient conditions whereas commercial producers use convective hot air dryers (Naidoo and Lindsay, 2010b). Currently, both small and large scale biltong producers use a variety of recipes and processes to accommodate consumer demands (Strydom and Zondagh, 2014).

The market for biltong is expanding both locally and internationally. However, there is no official estimation of the annual biltong production in South Africa (Strydom and Zondagh, 2014; Jones *et al.*, 2017). Biltong has gained popularity in regional and international markets such as Namibia, Australia, New Zealand, USA, Canada, the United Kingdom, Denmark, Netherlands, and Switzerland (Attwell, 2003). Nonetheless, it is difficult to fully exploit these export opportunities. A majority of the biltong processing factories in South Africa do not have an EU and hazard analysis and critical control points (HACCP) certification which are crucial to exporting biltong to EU countries (Attwell, 2003; Jones *et al.*, 2017). Consumer demand for consistent quality is also a problem for local and regional market, as well as the international markets.

Biltong is produced using several recipes and drying methods which results in a wide array of characteristics reported in literature (Van der Riet, 1976; Osterhoff and Leistner, 1984; Nortjé *et al.*, 2005; Petit *et al.*, 2014; Strydom and Zondagh, 2014; Jones *et al.*, 2017). Meat being processed to biltong is dried to a weight loss of 50 % or more to accommodate consumer preferences (Strydom and Zondagh, 2014). A number of studies have reported a wide range of moisture content (10 – 50 %) and water activity (0.54 – 0.93) (Van der Riet, 1976; Osterhoff and

Leistner, 1984; Nortjé *et al.*, 2005; Petit *et al.*, 2014; Jones *et al.*, 2017). The salt content and the pH of biltong ranges between 2 – 11 % and 4.8 – 5.9, respectively (Petit *et al.,* 2014; Strydom and Zondagh, 2014).

Petit *et al.* (2014) classified biltong as either dry or moist, based on their moisture content. Biltong with moisture content ranging between 21 and 25 % were classified as dry while those with moisture content ranging between 35 and 42 % classified as moist. Attwell (2003) and Nortjé *et al.* (2005) reported an increase in consumer preference towards biltong of higher moisture content. The high level of moisture content increases the risk of microbial attack which shortens the potential shelf-life of the biltong.

Although biltong is considered a safe product, some studies have raised concern over its microbial profile (Wolter *et al.*, 2000; Mhlambi *et al.*, 2010; Naidoo and Lindsay, 2010a; Naidoo and Lindsay, 2010b). These studies reported high levels of potential spoilage organisms as well as occasional presence of pathogens in biltong. The occurrence of pathogenic bacteria and toxigenic fungi such as *B. cereus* and *A. niger*, indicate the latent risk associated with biltong consumption (Allotey *et al.,* 2014).

Biltong can serve as a vector for foodborne pathogens such as *Listeria*, *Salmonella*, enterotoxigeni*c Staphylococci spp* and *E. coli* O157:H7 (Abong'o and Momba, 2009; Naidoo and Lindsay, 2010a; Naidoo and Lindsay, 2010b). Outbreaks of foodborne illnesses associated with the consumption of biltong have previously been reported (Allotey *et al.,* 2014). One fatality and at least two cases of severe gastroenteritis outbreaks attributed to *Salmonella* have been documented in South Africa while 17 individuals died in Botswana as a result of consuming contaminated biltong (Allotey *et al.,* 2014).

Microbial growth studies have demonstrated that salt, presence of organic acids, and spices are not in themselves inhibitory to microbial contamination in biltong (Burfoot *et al.*, 2010). The pH, water activity (a_w), and temperature used during the processing of biltong, fall within the tolerable limits for growth of some of the pathogenic microorganisms commonly found in biltong (Table 2.1). Therefore, it is important to critically examine the processes of making biltong with a view to improving its food safety while maintaining the nutritional properties and improving the energy efficiency of the process.

Table 2.1 Growth conditions for microorganisms identified in biltong

Microorganism	Growth conditions	Reference
Bacillus Cereus	Temperature range = 12-37 ℃ pH = 4.9-10.0 a_w = 0.93-0.99	ICMSF (1996)
Staphylococci Aureus	Temperature range = 37-45 ℃ pH = 4.0-10.0	Stewart (2003)
	a_w = 0.83-0.99	Montville and Matthews (2008)
Listeria monocytogenes	Temperature range= 30-37 ℃ pH = 4.0-9.6	Lado and Yousef (2007)
	a_w = 0.90-0.97	Lado and Yousef (2007)
	a_w = 0.81-0.97	Johnson *et al.* (1988)
Salmonella	Temperature range = 35-43 ℃ pH = 3.8-9.5 a_w = 0.93-0.99	Podolak *et al.* (2010)
Escherichia Coli O157:H7	Temperature range 30-40 ℃ pH = 4.4-9.0 a_w = 0.950-0.995	Desmarchelier and Grau (1997)

2.2 Biltong Processing

Biltong is processed in a series of steps beginning with the selection and preparation of meat, followed by marination, and finally drying of the meat.

2.2.1 Selection and preparation of meat

Meat from young carcasses is preferred since old animals produce tough, sinewy biltong. Muscles low in connective tissue from the round (buttock) and sometimes from the loin and tenderloin are used (Strydom and Zondagh, 2014). Topside (semimembranosus) and silverside (biceps femoris) are the most preferred muscles for making biltong. Other popular muscles include; eye of round (semitendinosus), thick flank (rectus abdominus), and fillet (psoas) (Jones *et al.*, 2017). The different cuts available from a whole beef carcass are shown in Figure 2.1

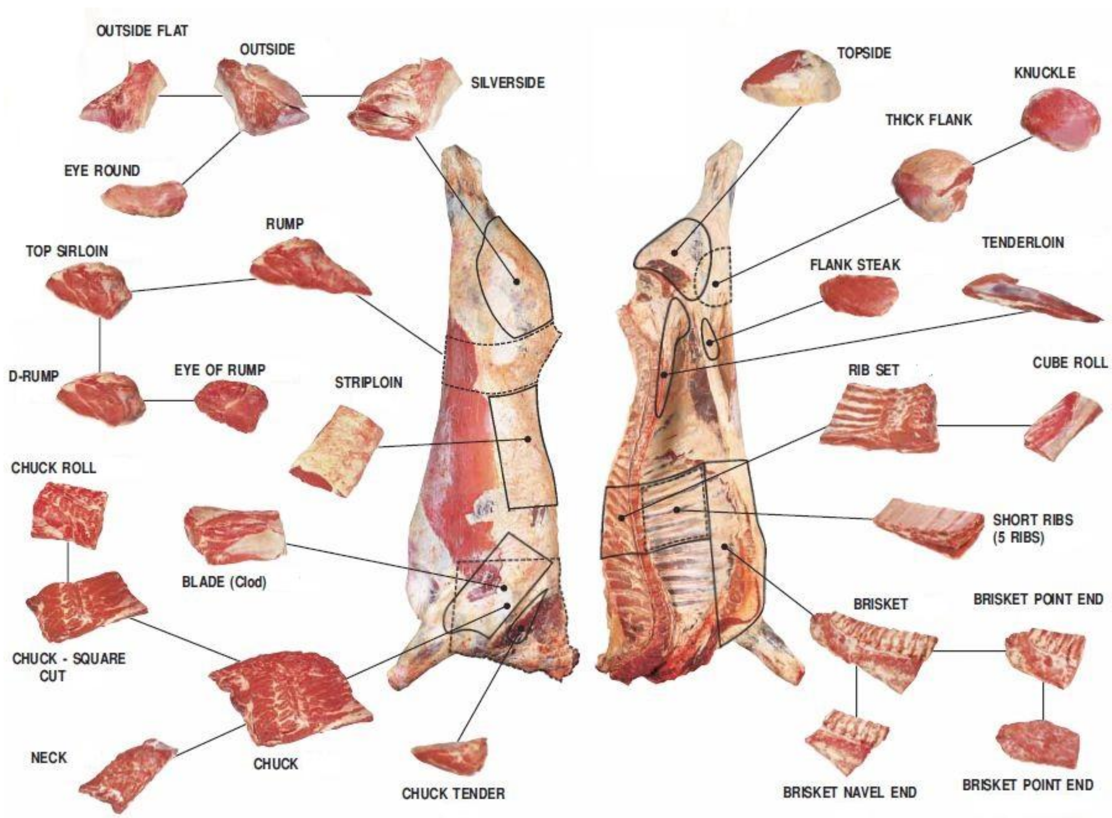

Figure 2.1 Beef cuts (Beef + Lamb, 2019)

The meat is generally cut along the meat fibres, into thin long strips (Van der Riet, 1982) as shown in Figure 2.2. The average dimensions of biltong strips range between 2.5 – 5 cm thick, 4 – 15 cm wide and 30 – 60 cm long (Van der Riet, 1982; Prior, 1984; Nortjé *et al.*, 2005; Naidoo and Lindsay, 2010b; Strydom and Zondagh, 2014). According to Jones *et al.* (2017), cutting the meat parallel to the meat fibres enhances the salt and spice absorption during marination of the meat, and improves the texture of the biltong. Eating quality and appearance of biltong could also be enhanced by cutting the meat diagonally across the grain (Jones *et al.*, 2017).

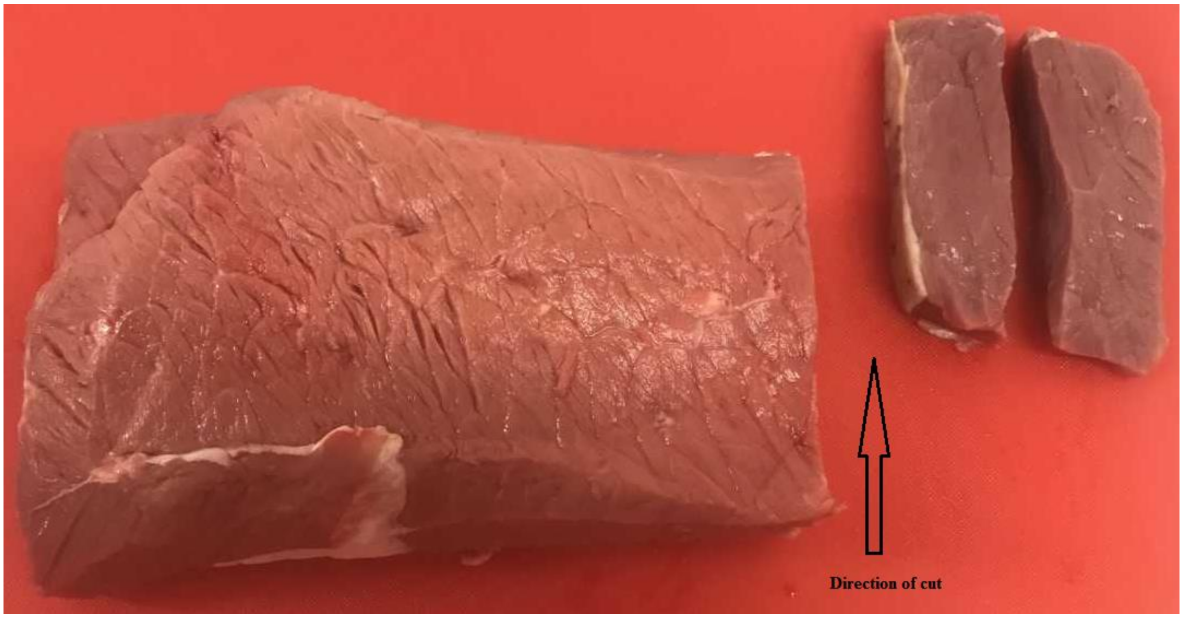

Figure 2.2 Piece of beef silverside cut along the meat fibres

While ostrich and game meat produce lean biltong, beef biltong can sometimes be fatty. Fatty biltong is gaining popularity with consumers (Strydom and Zondagh, 2014). However, excess fat should be trimmed off to avoid rancidity and low salt absorption by the meat (Strydom and Zondagh, 2014). According to Palumbo *et al.* (1977), fat can also decrease the water diffusivity of meat, consequently, increasing the drying time of meat during biltong production.

2.2.2 Marination of meat

Marination is the process of soaking meat in a liquid before drying. Salt and vinegar are the basic ingredients of a biltong marinade (Strydom and Zondagh, 2014). A vast array of seasonings such as; coriander, black paper, and brown sugar are included in the marinating mixture to provide biltong consumers with flavours (Burfoot *et al.*, 2010).

Salt acts as a curing agent during marination. The salt lowers the moisture content of meat through osmotic dehydration (Guizani *et al.*, 2008; Hui, 2012). Moreover, the salt reduces the water activity of the meat by immobilising the water molecules, making them unavailable for chemical, enzymatic, or microbial activity. Adding a 2 % salt solution to meat can potentially reduce the water activity of meat to between 0.97-0.93 (Toldrá, 2010). Salt solution of between

2.5 – 4.0 % is normally used for biltong (Van der Riet, 1976; Van der Riet, 1982). This range of salt concentration can reduce the water activity of meat to ≤ 0.93, thus, inhibiting the growth of bacteria responsible for meat spoilage (Lawrie, 2017).

Similar to salt, vinegar is added to influence the flavour, inhibit microbial growth and influence water holding capacity of biltong (Naidoo and Lindsay, 2010b; Strydom and Zondagh, 2014). Brown spirit vinegar and apple cider vinegar are commonly used in biltong production (Jones *et al.*, 2017). The level of vinegar added to biltong ranges between 3 and 6 % (Naidoo and Lindsay, 2010b). The dilute acetic acid contained in vinegar reduces the ionic strength of meat by lowering the pH of the meat proteins from 6.0 to around 5.0 which is the isoelectric point of meat proteins (Cheng and Sun, 2008; Hui, 2012; Brewer, 2014). The minimum water holding capacity of meat occurs at the isoelectric point (Brewer, 2014). The meat losses water through drip as the pH moves closer to the isoelectric point (Miller, 2014). The variations in the water holding capacity of meat with changing pH is shown in Figure 2.3.

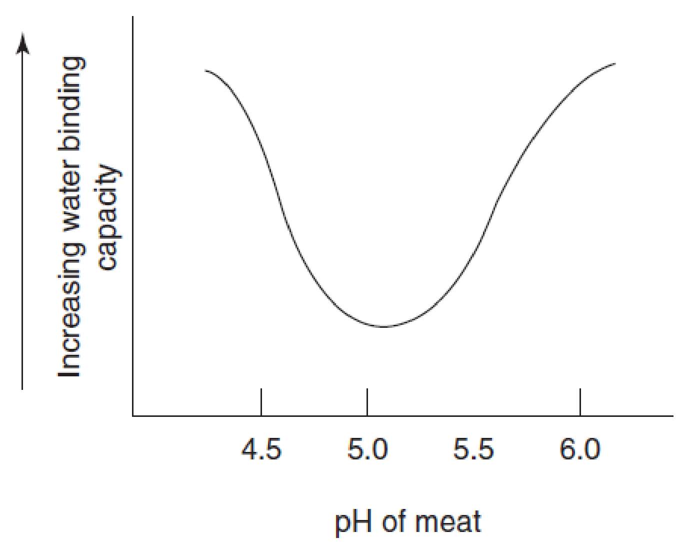

Figure 2.3 Effect of pH on water holding capacity of meat (Miller (2014)).

Biltong marinade also includes an array of seasonings such as black pepper, brown sugar, and coriander. The marinade is applied in several ways depending on the scale of production. For domestic biltong production;

(i) the meat can be dipped in dry spices (Van der Riet, 1976), or
(ii) dipped in dry spices then dipped vinegar (Leistner, 1987), or
(iii)dipped in vinegar, drained, then dipped in dry spices (Naidoo and Lindsay, 2010b).

In the case of commercial biltong production, the meat pieces are dipped in a marinade made of a mix of vinegar and spice. Tumbling is done immediately after to ensure the meat is fully coated with marinade (Naidoo and Lindsay, 2010b). The meat is refrigerated at 4 ℃ for 18 – 20 hours prior to drying (Burfoot *et al.*, 2010).

2.2.3 Drying of meat

Traditionally biltong is produced by hanging marinated pieces of meat to dry under ambient conditions. Currently, biltong drying units range from simple domestic dryers to high capacity commercial dryers (Burfoot *et al.*, 2010; Naidoo and Lindsay, 2010b). Commercial dryers are predominantly temperature controlled with only a few having both temperature and humidity control (Jones *et al.*, 2017). A summary of various drying equipment and their process parameters is given in Table 2.2.

Table 2.2 Biltong drying equipment and process parameters (after Jones *et al.* (2017))

Equipment	Temperature (℃)	RH (%)	Air Velocity (m/s)	Time (days)	Reference
Homemade dryer with a bulb	25	-	-	4	Naidoo and Lindsay (2010b)
Environmental chamber	20-22	38-64	-	17-26	Burnham *et al.* (2008)
Drying cabinet	35	-	-	-	Dzimba *et al.* (2007)
Drying cabinet	28-32	70	-	2	Nortjé *et al.* (2005)
Drying cabinet	35	30	3	6	Taylor (1976)

Commercial biltong dryers use hot air to dry the meat to the desired moisture content. Hence, the hot air parameters *viz*. temperature, relative humidity, and velocity must be well chosen to obtain the desired product. Generally, the drying air temperature used when processing biltong ranges from 25 to 35 ℃. There is little scientific literature on the levels of drying air relative humidity and velocity that is appropriated for processing biltong (Table 2.2). It is necessary to characterise the hot air drying parameters (Temperature, relative humidity, and velocity) since they have a huge implication on the drying kinetics of meat during biltong processing, the quality of biltong produced, and the energy consumption (Chabbouh *et al.*, 2011; Hii *et al.*, 2014; Ahmat *et al.*, 2015; Kucerova *et al.*, 2015; Petrova *et al.*, 2015).

2.3 Hot Air Drying

HAD is an energy intensive drying method. Drying products using HAD is slow and degrades the quality of the dried product (Ratti, 2001; Sharma and Prasad, 2001). HAD has been associated with deleterious physical and nutritional quality effects such as loss of colour, loss of heat sensitive nutrients, and deformation or even internal structure damage (Kowalski and Mierzwa, 2009).

HAD imposed changes such as case hardening (Bellagha *et al.*, 2007) and shrinkage (Duan *et al.*, 2011) may be of concern during biltong production. Case-hardening is caused by rapid drying due to high drying temperatures coupled with low relative humidity and high air velocity. The high surface evaporation rates dry out the surface quickly and prevents the moisture inside the meat from moving out (Serra *et al.*, 2005).

During HAD of meat products, the loss of water and mobility of the solid matrix makes the meat to shrink which causes stress in the cellular structure of the meat (Mayor and Sereno, 2004). Shrinkage can also be caused by the drying of collagen transforming it into soluble gelatin. Prolonged heating and drying causes gelatin to bind the muscle fibres, forming an intact structure, which causes the meat to bend, and become tough (Huang and Nip, 2001). This phenomenon may result in undesirable biltong that is difficult to eat.

HAD is extensively used in the drying of meat products such as pork and beef (Poligné *et al.*, 2001; Banout *et al.*, 2012; Strydom and Zondagh, 2014). However, the low thermal conductivity and case hardening of the material decelerate the moisture migration during HAD of meats. This results in longer drying time and increases energy consumption (Soydan Karabacak *et al.*, 2014). The need to heat up the drying air coupled with low thermal conductivity of the material, further amplifies the energy demands (Łechtańska *et al.*, 2015). The thermal energy necessary for drying can, alternatively, be supplied through electromagnetic waves such as infrared and microwaves. Infrared heating transfers energy directly to the product without heating the surrounding air, thus, improving the energy efficiency and reducing the drying time (Riadh *et al.*, 2015).

2.4 Infrared Drying

Infrared (IR) radiation can replace or supplement HAD to enhance the overall efficiency of the drying process. IR radiation transfers thermal energy in the form of electromagnetic waves which are converted into heat when they impinge on the surface of a product (Krishnamurthy *et al.*, 2008b). IR radiation generates heat directly inside the product providing volumetric heating (Khir *et al.*, 2011; Riadh *et al.*, 2015). This positively impacts the energetic, exergetic, and heating efficiency (Onwude *et al.*, 2016). Infrared heating results in uniform product heating, reduced processing time, lower energy consumption, and better nutritional value of the processed product (Pan *et al.*, 2014; El-Mesery and Mwithiga, 2015). Consequently, IR heating has been applied widely in recent years in different thermal processing operations in the food industry such as pasteurization, drying, and frying (Riadh *et al.*, 2015).

2.4.1 Effect of IR on food quality

The suitability of IR for drying a given food product depends on the quality (sensory, nutritional and functional) attributes of the final product. Some quality loss may be observed in heat sensitive products such as fruits and vegetable during IR drying (Pan and Atungulu, 2010). Nonetheless, IR drying generally results in minimal quality losses in the final product (Riadh *et al.*, 2015). A summary of some of the quality attributes of different food materials subjected to IR drying or heating is shown in Table 2.3.

Table 2.3 Quality attributes of food subjected to IR treatment

Method	Food	Food quality	Reference
IR drying	Beef jerky	Improved dehydration efficiency	Li *et al.* (2018)
IR drying	Biltong	Improved colour and texture	Cherono *et al.* (2016)
IR drying	Beef	Similar taste and colour to HAD	Burgheimer and Nelson (1971)
IRHAD IR and heat pump	Longan fruit	less shrinkage and less hardness	Nathakaranakule *et al.* (2010)
IRHAD	Onion	Better rehydration capacity	Kumar *et al.* (2005)
IR freeze drying	Yam	High rehydration ratio	Lin *et al.* (2007)
IR drying	Lentils	Better rehydration capacity Dark colour	Arntfield *et al.* (2001)
IR drying	Onion	Dark colour	Gabel *et al.* (2006)
IR heating	Deli turkey	Roasted appearance and brown colour	Muriana *et al.* (2004)
IR drying	Noodles	Reduced cooking loss Reduced loss in total organic matter	Basman and Yalcin (2011)

2.4.2 Effect of IR on food safety

Food safety is a key concern to consumers and processers alike. Food safety can be compromised by enzymes or microorganisms that degrade the food. IR heating can be used for enzyme inactivation to limit food spoilage (Krishnamurthy *et al.*, 2008b). The enzymatic reactions involving lipases and α amylases are affected by IR radiation at a bulk temperature of 30 to 40 °C (Kohashi *et al*., 1993; Rosenthal *et al.*, 1996; Sawai *et al.*, 2003). Kouzeh-Kanani *et al.* (1982) reported a 95.5 % inactivation of lipoxygenase (an enzyme responsible for deterioration in soybeans) within 60 s of IR treatment. The findings by Van Zuilichem *et al.* (1986) showed that far IR successfully inactivated enzymes responsible for the development of off-flavours in peas, while Sawai *et al.* (2003) reported that IR treatment inactivated several enzymes and bacteria.

Nonchemical decontamination of pathogenic microorganisms is possible through proper application of IR heating (Pan *et al.*, 2014). The efficacy of using IR heating for food safety enhancement has been studied for various applications such as pathogen inactivation (Krishnamurthy *et al.*, 2010), milk sterilization (Krishnamurthy *et al.*, 2008a; Krishnamurthy *et* *al.*, 2008b), fruit surface decontamination (Tanaka *et al.*, 2007; Tanaka and Uchino, 2010), almond pasteurization (Bari *et al.*, 2009; Yang *et al.*, 2010), rice disinfestation (Pan *et al.*, 2008), and improving the microbial quality of biltong (Cherono *et al.*, 2016).

IR heating can inactivate bacteria, spores, yeast, and mold in both liquid and solid foods (Rastogi, 2012). Sawai *et al.* (2006) indicated that the death rate constant of *E coli* is higher for far-IR heating than conductive heating. Jun and Irudayaraj (2003) showed that selective far-IR heating (5.88 to 6.66 µm) resulted in 40 % increase in inactivation of *A. niger* and *F. proliferatum* in cornmeal as compared to normal IR heating. The absorption of energy by the fungal spores increased during selective heating, leading to a higher lethality rate (Jun and Irudayaraj, 2003). Conversely, Hamanaka *et al.* (2006) reported that pathogen inactivation was higher at IR radiations of shorter than longer wavelength (0.95 > 1.1 >1.15 µm). The foregoing studies demonstrate that inactivation efficiency using IR is dependent on the radiation spectrum.

IR radiation has a poor penetration capacity which makes it mostly suited for surface decontamination (Riadh *et al.*, 2015). The effect of IR radiation on the microbial inactivation diminishes as the sample thickness increases (Sawai *et al.*, 1997). Decreasing the sample thickness accelerates the inactivation of spores, *E. coli*, and *S. aureus* (Hashimoto *et al.*, 1992; Sawai *et al.*, 1997; Sawai *et al.*, 2006). Rosenthal *et al.* (1996) indicated that IR heating at 70 °C for 5 min effectively reduced the growth of yeasts and fungi on the surface of cheese without affecting the quality of the product. In related studies, James *et al.* (2002) demonstrated the potential use of IR treatments to pasteurize the surface of eggs without significantly raising the interior temperature that would otherwise cause coagulation of egg contents.

Huang (2004) indicated the suitability of IR for the surface pasteurization of turkey frankfurters. IR heating to 80, 75, and 70 °C reduced the counts of *L. monocytogenes* by 4.5, 4.3, and 3.5 log units, respectively. IR pasteurization can also be used to effectively inactivate *L. monocytogenes* and *E. coli* on ready-to-eat meats such as hotdogs (Huang and Sites, 2008) and biltong (Cherono *et al.*, 2016), respectively.

IR drying is a promising method that is best suited for thin, flat products (Riadh *et al.*, 2015). It is not easily applicable to food products with irregular shape and sizes as this would result in uneven heating (Krishnamurthy *et al.*, 2008b). Furthermore, prolonged exposure to IR heat can adversely affect the physical, mechanical, chemical, and functional properties of biological material (Fasina *et al.*, 1996; Fasina *et al.*, 1997). These limitations can be overcome by combining IR heating with other drying methods (Riadh *et al.*, 2015). Some typical applications of IR heating combined with other drying methods include; vacuum IR drying of carrots (Nimmol *et al.*, 2005), IR microwave drying of beetroot (Kowalski and Mierzwa, 2009), and combined IRHAD of sweet potatoes (Onwude *et al.*, 2018).

Application of combined electromagnetic radiation and convective heating is more efficient over radiation or convective heating alone (Krishnamurthy *et al.*, 2008b). According to Afzal *et al.* (1999), a combined IR and HAD (IRHAD) has a more synergistic effect which results in improved physical and nutritional quality as well as energy conservation, compared to the independent use of either IR or HAD. Findings by Hebbar *et al.* (2004) confirmed that the synergistic effect of IR and hot air promotes rapid heating that results in a higher rate of mass transfer during IRHAD of vegetables. Hebbar *et al.* (2004) observed a 48 % reduction in drying time and improved energy utilization efficiency in IRHAD of potato and carrot.

2.4.3 IR drying kinetics

The drying kinetics of agricultural materials depend on the process conditions and material properties (Arsoy, 2008). The IR energy is transferred from the IR emitter to the material surface without heating the surrounding air. Hence, almost all of the energy coming from the IR emitter is delivered to the material (Wang and Sheng, 2004). Consequently, the power density in IR drying is 6–10 times greater than in HAD (Abukhalifeh *et al.*, 2005).

Applying a high power density to the material can significantly reduce the drying time. Bualuang *et al.* (2013) observed that increased IR intensity shortened drying time due to higher heat and mass transfer coefficient and increased rate of diffusion. Similar findings were made by Chen *et al.* (2012) and Ponkham *et al.* (2012). According to Doymaz (2012) the IR density directly relates to the effective diffusivity and inversely affects the drying time. Findings by Nasiroglu and Kocabiyik (2009) showed that the increase in the infrared power and the decrease in the air velocity caused a reduction in the drying time of red pepper.

The drying behavior of food subjected to IR radiation is also dependent on the distance between the IR emitter and the sample being dried (Ježek *et al.*, 2008; Kocabiyik and Tezer, 2009). An increase in the distance between the IR emitter and the sample increases drying time due to reduction of energy transfer to the product (Sadin *et al.*, 2014).

Nathakaranakule *et al.* (2010) showed that the drying rate of longan fruit using IRHAD depended on product thickness, infrared power level, infrared intensity, and drying temperature. A critical assessment of the drying parameters of interest is necessary to optimize the drying processes. Mathematical modelling provides an effective way of assessing and manipulating the process parameters to determine the optimal drying conditions.

2.5 Modelling the Heat and Mass Transfer during Infrared Drying

Modelling of thermal food processes is critical in evaluating the safety and performance of the process (Riadh *et al.*, 2015). Mathematical models and simulations represent a powerful alternative to the traditional, time-consuming temperature/moisture measurements, and microbiological and food quality analyses (Feyissa *et al.*, 2009). Moreover, the models can be used to predict the influence of the process variables on the drying kinetics and quality parameters of dried products (Pawar and Pratape, 2017). Drying processes can be modelled using distributed models or lumped parameter models (Erbay and Icier, 2010).

2.5.1 Distributed models

Distributed models take account of the simultaneous heat and mass transfer. These models can predict the temperature and moisture gradient in a product by considering both the external and internal heat and mass transfer (Erbay and Icier, 2010). The distributed models depend on the Luikov equations (Equation 2.1 – 2.3) which are derived from Fick’s second law of diffusion (Luikov, 1975).

$$\frac{\delta M}{\delta t} = \nabla^2 K_{11}M + \nabla^2 K_{12}T + \nabla^2 K_{13}P \tag{2.1}$$

$$\frac{\delta T}{\delta t} = \nabla^2 K_{21}M + \nabla^2 K_{22}T + \nabla^2 K_{23}P \tag{2.2}$$

$$\frac{\delta P}{\delta t} = \nabla^2 K_{31}M + \nabla^2 K_{32}T + \nabla^2 K_{33}P \quad (2.3)$$

Where:

t = drying time (s),

M = moisture content of the product (kg of water/kg of sample),

T = temperature of the product (º K),

P = pressure (Pa),

K_{11}, K_{22}, K_{33} = phenomenological coefficients, and

K_{12}, K_{13}, K_{21}, K_{23}, K_{31}, K_{32} = coupling coefficients.

According to (Brooker *et al.*, 1992), the effect of pressure can be neglect, giving rise to the modified Luikov equations (Equations 2.4 and 2.5).

$$\frac{\delta M}{\delta t} = \nabla^2 K_{11}M + \nabla^2 K_{12}T \quad (2.4)$$

$$\frac{\delta T}{\delta t} = \nabla^2 K_{21}M + \nabla^2 K_{22}T \quad (2.5)$$

The modified Luikov equations cannot be solved analytically. Their numerical solution can be obtained using the finite element method (Özilgen and Özdemir, 2001).

2.5.2 Lumped parameter models

Lumped parameter models assume a uniform product temperature distribution, that is equal to the drying air temperature (Erbay and Icier, 2010). Hence, the Luikov equations are further modified as presented in Equations 2.6 and 2.7.

$$\frac{\delta M}{\delta t} = K_{11} \nabla^2 M \quad (2.6)$$

$$\frac{\delta T}{\delta t} = K_{22} \nabla^2 T \quad (2.7)$$

The phenomenological coefficients, K_{11} and K_{22} become the effective moisture diffusivity (D_{eff}) and thermal diffusivity (α), respectively. For a constant D_{eff} and α, Equations 2.6 and 2.7 can be rewritten as shown in Equation 2.8 and 2.9 (Ekechukwu, 1999).

$$\frac{\delta M}{\delta t} = D_{eff}[\frac{\delta^2 M}{\delta x^2} + \frac{a_1}{x}\frac{\delta M}{\delta x}] \quad (2.8)$$

$$\frac{\delta T}{\delta t} = \alpha[\frac{\delta^2 T}{\delta x^2} + \frac{a_1}{x}\frac{\delta T}{\delta x}] \quad (2.9)$$

Where:

a_1 = 0, 1, or 2 for planar, cylindrical, and spherical geometry, respectively, and

D_{eff} = effective moisture diffusivity ($m^2 . s^{-1}$).

The assumption of uniform temperature distribution that is equivalent to the ambient temperature causes errors which can be minimised by reducing the thickness of the product (Erbay and Icier, 2010). Hence the thin layer drying models.

2.5.3 Thin layer drying models

Thin layer drying models assumes isothermal conditions during the drying process, thus they only describe the mass transfer. The fundamental assumptions (Erbay and Icier, 2010) made during the development of thin layer drying models enable the analytical solution of Equation 2.8, as shown in Equation 2.10 (Crank, 1979).

$$\mathrm{MR} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} \times \exp\left[-(2n+1)^2\frac{\pi^2 D_{eff} t}{b^2}\right] \quad (2.10)$$

Where:

MR = moisture ratio, and

b = half thickness of the sample (m).

The MR is calculated using Equation 2.11 (Ertekin and Firat, 2017).

$$\mathrm{MR} = \frac{M(t)}{M_0} \quad (2.11)$$

Where:

M_0 = initial moisture content of the sample (kg of water/kg of dry solid), and

M(t) = moisture content of the sample at time t (kg of water/kg of dry solid).

The thin layer drying models describe the variation of MR with drying time. Several thin layer drying models have been developed and used to describe the drying of different food materials (Ertekin and Firat, 2017). The appropriateness of a given model is determined through regression analysis of the experimental data and the selected models (Kucuk *et al.*, 2014). The best models are chosen based on high coefficient of determination (R^2) and modeling efficiency, and low values for mean bias error (MBE), root mean square error (RMSE), chi square (χ^2), and the sum of residuals. Some of the thin layer drying models used to describe the IR drying of food materials are listed in Table 2.4.

Thin layer drying models are practical and give acceptable results. However, they are limited to the prediction of average moisture content and drying time (Erbay and Icier, 2010). Modelling the drying process using distributed models provides a better understanding of the drying process and gives more accurate results compared to the thin layer drying models (Özilgen and Özdemir, 2001).

Table 2.4 Summary of thin layer drying models used in IR drying

	Drying method	Food material	Model	Model Equation	Reference
1	IRHAD	Onion slices	Modified page	$MR = K\exp(-t/d^2)^n$	Kumar *et al.* (2006)
2	IR	Sweet potato slices	Logarithmic model	$MR = a\exp(-kt)$	Doymaz (2012)
3	IRHAD	Murta berries	Midili et al.	$MR = a\exp(-kt^n) + bt$	Puente-Díaz *et al.* (2013)
4	IRHAD	Wine grape pomace	Midili et al.	$MR = a\exp(-kt^n) + bt$	Sui *et al.* (2014)
5	IR	Peach slices	Midili et al.	$MR = a\exp(-kt^n) + bt$	Doymaz (2014)
6	IR	Biltong	Diffusion approximation model	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Cherono (2014)
7	IR	Mint leaves	Modiffied Henderson and Pabis-II	$MR = a\exp(-kt^n) + b\exp(-gt) + C\exp(-ht)$	Ertekin and Heybeli (2014)
8	IRHAD	Shredded squids	Page model	$MR = \exp(-kt^n)$	Wang *et al.* (2014)
9	IR	Jujube	Two term model	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	Chen *et al.* (2015)
10	IRHAD	Green peas	Three term model	$MR = a\exp(-k_0t) + b\exp(-k_1t) + C\exp(-k_2t) + d$	Eshtiagh and Zare (2015)
11	IRHAD	Tomato slices	Midili et al.	$MR = a\exp(-kt^n) + bt$	Sadin *et al.* (2017)

2.5.4 Heat and mass transfer modelling

The heat and mass transfer play an important role in drying of products (Srikiatden and Roberts, 2007). The temperature and water content inside a solid food product vary in space and time during heat treatment (Feyissa *et al.*, 2009). Their entire history and spatial distribution influence the quality and the safety of the processed foods. A solid food system undergoes several changes during drying. The food system undergoes phase changes during evaporation of water (Adler-Nissen, 2007; Datta, 2007), shrinkage and pore formation during drying processes (Yang *et al.*, 2001; Talla *et al.*, 2004; Tornberg, 2005), crust formation (Jefferson *et al.*, 2006), and colour change (Purlis, 2010). These changes may influence the heat and mass transfer mechanisms directly (e.g., phase change, formation of porous media) or influence the heat and mass transfer properties such as thermal conductivity, diffusivity and permeability (Feyissa *et al.*, 2009).

a) Heat transfer

The heating of solid foods involve external and internal heat transfer processes (Therdthai and Zhou, 2003). External heat transfer takes place between the heating medium (fluid or solid) and the solid food, whereas internal heat transfer takes place within the solid food itself. The external heat transfer is often considered as the boundary condition governing heat transfer (Bird *et al.*, 2001). A solid food and a heating medium exchange heat at their boundaries by conduction, convection or radiation, or a combination of these mechanisms (Gupta, 2001; Therdthai and Zhou, 2003).

The governing equations for the heat transfer inside a solid food is based on the principle of conservation of energy (Equation 2.12) (Bird *et al.* 2001).

$$\rho_p c_{p,p} \frac{\delta T}{\delta t} = \nabla\left(k_p \nabla T\right) - \rho_w c_{p,w} u \nabla T \tag{2.12}$$

Where:

T = temperature product (° K),

ρ_p = density of product (kg.m^{-3}),

ρ_w = density of water (kg.m^{-3}),

$c_{p,p}$ = specific heat of product (J.kg^{-1}.K^{-1}),

$c_{p,w}$ = specific heat of fluid ($J.kg^{-1}.K^{-1}$),

k_p = thermal conductivity of product ($W.m^{-1}.K^{-1}$),

u = velocity of water ($m.s^{-1}$), and

t = time (s),

In the case of electromagnetic heating such as IR, a volumetric heat generation term Q ($W.m^{-3}$) is added to Equation 2.12 to give Equation 2.13 (Pan *et al.*, 2014).

$$\rho_p c_{p,p} \frac{\delta T}{\delta t} = \nabla(k_p \nabla T) - \rho_f c_{p,f} u_f \nabla T + Q \qquad (2.13)$$

Modeling of infrared heat transfer is challenging because of the complexity of optical characteristics, radiative energy extinction, and combined conductive and/or convective heat transfer phenomena (Krishnamurthy *et al.*, 2008a; Pan and Atungulu, 2011). IR energy absorption/penetration and extinction in food materials is critical in modeling (Prakash, 2011; Tanaka and Uchino, 2011). IR power absorption by food can be considered as an exponential decay function penetrating from the surface to the interior of food materials (Datta and Ni, 2002; Tanaka and Uchino, 2011). Consequently, the IR power absorption appears as a volumetric heat source term (Q) in the energy balance equation (Onwude *et al.*, 2018). Alternatively, a zero penetration depth can be assumed. In which case, all the IR energy is absorbed at the food surface, thus Q (Equation 2.13) will be zero (Li, 2012). Therefore, the heat flux of IR radiation is incorporated in the boundary condition at the modeled food surface (Li, 2012). At shallow (<1 mm) IR penetration depths, no significant difference has been found between these two assumptions in terms of the accuracy of temperature prediction (Prakash, 2011; Tanaka and Uchino, 2011).

b) Mass transfer

Drying of foods is also characterized by mass loss mainly in the form of water (Mondal and Datta, 2008; Sumnu and Sahin, 2008). The transport of water is driven by the gradients in the water concentration. Water migrates during the heating of solid foods by different mechanisms: molecular diffusion, pressure driven flow, capillary diffusion, and thermo-diffusions (Srikiatden and Roberts, 2007). The governing equation for mass transfer in solid foods is based on the principle of conservation of mass as shown in Equation 2.14 (Bird *et al.*, 2001; Celma *et al.*, 2008; Ponkham *et al.*, 2012).

$$\frac{\delta M}{\delta t} = \nabla(D_{eff}\nabla M) - u\nabla M \qquad (2.14)$$

Where:

M = moisture concentration in the product (kg of water/kg of sample),

D_{eff} = effective diffusivity ($m^2.s^{-1}$), and

u = velocity of water.

Water transport models based on Fick's equation of diffusion, such as Equation 2.3, assumes that diffusion is the only mode of water transport (Feyissa *et al.*, 2009). The ensuing transient diffusion equation for water transport is solved using experimentally determined effective diffusivity (Shilton *et al.*, 2002; Wang and Singh, 2004; Kondjoyan *et al.*, 2006). Feyissa *et al.* (2009) argued that not all water transport during heating of solid foods can be attributed to diffusion. Moreover, the use of effective diffusivity does not yield insight into the prevalent transport mechanisms (Halder *et al.*, 2011). Other phenomena such as pressure-driven flow is critical during intensive heating such as roasting of meat. According to Srikiatden and Roberts (2007) better predictions of moisture distribution for drying of porous materials could be obtained if Fick's diffusion equation is expressed in terms of vapor pressure gradient as the driving force for diffusion rather than moisture concentration gradient (Equation 2.15).

$$\frac{\delta p_{vs}}{\delta t} = \frac{\delta}{\delta x}\left(P_D \frac{\delta p_{vs}}{\delta x}\right) \qquad (2.15)$$

where

p_{vs} = water vapor pressure, and

P_D = moisture dependent vapor diffusion coefficient.

Moisture can also be transported through evaporation-condensation. This is a coupled internal heat and mass transfer mechanism where mass is transferred in the vapor state and heat is gained and lost by condensation and evaporation, respectively (Srikiatden and Roberts, 2007). Harmathy (1969) reported that evaporation-condensation was the dominant mechanism of heat and mass transfer in a porous system during the falling rate drying period. He obtained complete moisture, temperature and pressure distributions throughout the drying of a brick slab using a set of second order partial differential equations with appropriate initial and boundary conditions.

According to Datta (2007), heating of solid food is often accompanied by the evaporation of water. Water evaporates entirely inside the food (local evaporation) during intense heating. Incorporation of local evaporation into the model of heat and mass transfer requires significant reformulation of the model (Datta, 2007; Huang *et al.*, 2007). It is difficult to determine the evaporation rate which is an important variable that determines the heat loss and the rate of water that is evaporated during heating of solid foods at higher temperatures (Huang *et al.*, 2007).

c) Coupled heat and mass transfer

During drying, the heat and mass transfer take place simultaneously. A number of coupled heat and mass transfer models have been developed to simulate the IR drying of food material. Liu *et al.* (2014) developed a mathematical model of heat and mass transfer based on energy and diffusion equations, to simulate vacuum far-infrared drying of potato slices. Ranjan *et al.* (2002) used the control volume formulation to develop a three-dimensional model for IR heating based on moisture transfer, heat and pressure equations. A combined heat and mass transfer model was developed by Rudobashta *et al.* (2014) to analyze the dynamics of oscillating IR heating of a layer of seeds. Islam *et al.* (2007) presented results of a simple diffusion-based model to predict the drying performance of a pilot-scale twin-drum dryer.

A multiphase model developed by Datta and Ni (2002) for energy and moisture determination could also simulate the temperature and moisture profiles of food during drying. Dagerskog (1979) successfully predicted the temperature distribution of slices of beef undergoing IRHAD. Salagnac *et al.* (2004) developed a one-dimensional model based on temperature and moisture content of a porous material. The Salagnac *et al.* (2004) model successfully described the heat and mass transfer during IRHAD of a rectangular-shaped porous material. However, none of these models considered key drying factors such as evaporation, shrinkage dependent moisture distribution, and variable material properties.

Kumar *et al.* (2015) used both evaporation and shrinkage dependent diffusivity to successfully develop a coupled heat and mass transfer model for HAD of banana. In a related study, Kumar *et al.* (2016) developed couple multiphase heat and mass transfer model for apple undergoing intermittent combined microwave and HAD. The model considered evaporation, shrinkage dependent effective moisture diffusivity and microwave heat source based on Lambert's law. It acceptably explained the drying process and mechanism of intermittent microwave and HAD of an apple. Similarly, Onwude *et al.* (2018) developed a coupled heat and mass transfer model to describe the mechanism of combined IRHAD of sweet potato by considering evaporation, shrinkage dependent moisture distribution and IR heating source based on Lambert's law.

The heat and mass transfer models consist of sets of partial differential equations that cannot be solved analytically (Özilgen and Özdemir, 2001). The numerical solutions to these equation are obtained using the finite difference, finite element, or finite/control volume methods (Srikiatden and Roberts, 2007).

d) Computational methods

Industrial food-processing applications require a realistic representation of the food material and the drying process to guarantee more precision. Consequently, multidimensional models have been increasingly investigated in order to gain more insight into IR heating characteristics (Tanaka *et al.*, 2007; Dhall *et al.*, 2009; Prakash, 2011). Tanaka *et al.* (2007) used a three-dimensional geometry of a real strawberry to simulate IR radiation for the surface decontamination. The complex view factors caused by the irregular shape of the strawberry, were quantified using the Monte Carlo ray tracing approach integrated in ANSYS software (Tanaka *et al.*, 2007). Howell *et al.* (2015) outlines the different mathematical routines developed for computing the radiation view factors of complex geometric configurations for multidimensional models. IR irradiance flux calculated from the view factors on strawberry surface was incorporated into a Neumann boundary condition to solve the heat transfer problem in strawberry (Tanaka *et al.*, 2007).

A three-dimensional geometric model developed by Li *et al.* (2011) accurately described the variability in shape and size of tomatoes. The modeled tomatoes were used to predict the temperature distributions on the surface and within a tomato undergoing a double-sided IR heating for a dry-peeling process. IR irradiance of the tomato surface was calculated based on differential view factors using the hemicube method implemented in COMSOL software.

Onwude et al. (2018) also used COSMOL to solve the coupled heat and mass transfer during a combined IRHAD of sweet potatoes.

2.6 Discussion and Conclusion

The increased production and consumption of biltong both locally and internationally makes biltong an economically important product in the South African meat industry. Quality conscience export markets such as those in Europe and the USA highlight the need to standardise the production methods of biltong. It is evident from the literature reviewed that there is limited guidance on production of biltong. Consequently, there is a wide spectrum of biltong characteristics. Moreover, existing documentation highlight serious food safety concerns. The food safety concerns and inconsistent quality characteristic hamper the expansion of existing markets and acquisition of new markets for biltong.

Vinegar and a reduction in water activity are the key ways of preventing microbial and fungal contamination. The addition of vinegar and other ingredients in the marinating mixture lowers the pH from 6.0 in raw meat to approximately 4.8 – 5.9 in biltong. This range of pH (4.8 – 5.9) falls within the tolerable limits of most microorganisms found in biltong (Table 2.1, §2.2.3). Thus, the addition of vinegar is not enough to inhibit the growth of spoilage and potentially toxic microorganism in biltong.

Reducing the water activity effectively limits microbial and fungal activity. The addition of salt at the recommended levels of 2.5 - 4.0 % in the biltong marinade can reduce the water activity of meat to ≤ 0.93. This reduction in water activity inhibits the growth common bacteria found in biltong. Further reduction in water activity through drying, is necessary to inhibit fungal growth. Drying meat to a weight loss of 50 % reduces the water activity to ≤ 0.65 in the resulting biltong. Hence, inhibiting all microbial and fungal growth. Changing consumer preference towards high moisture biltong increases the risk of microbial and fungal attack. The possibility of rehydration due to improper storage or packaging may also provide suitable environment to revive microbial and fungal activity in biltong.

Alternative drying methods such as IR have shown potential in decontamination of food products without compromising their quality. IR energy is absorbed by the bacteria and fungal spores, leading to a high lethality rate. This contrasts with hot air drying which inactivates the microorganisms by reducing the water activity in the meat.

A combined Infrared and hot air drying could be a possible alternative drying method for biltong production. The synergistic effect between the IR and hot air improves the energy efficiency and reduces the drying time. The literature reviewed indicate that IRHAD results in dried products with better physical and nutritional quality. Nonetheless, there is need for sufficient information regarding the drying process variable (temperature, relative humidity and air velocity) and the corresponding quality attributes to ascertain the suitability of IRHAD for biltong production.

Mathematical models provide great insight into the interaction between the process variables, their influence on the drying kinetics and quality of the dried products. Thin layer drying models have been used to model the dying of several agricultural products. These models are practical and provide acceptable results. However, a better understanding of the drying process is achieved by modelling the external and internal heat and mass transfer during the drying of agricultural products.

Previous research have reported the coupled heat and mass transfer models for meat under HAD but no studies have been done on modelling the coupled heat and mass transfer of IRHAD of meat. It is necessary to investigate and model the mechanisms of heat and mass transfer in meat during the processing of biltong. Realistic representation of the food material and the drying process can guarantee precision when simulating industrial food process operations. Finite element softwares like ANSYS Fluent and COMSOL enable the formulation and solution of the complex multidimensional heat and mass transfer equations. Thus, providing a comprehensive spatial and temporal distribution of the temperature and moisture content profile within the food material.

In summary, IRHAD could be a possible alternative to solving the food safety concerns of biltong. Modelling the coupled heat and mass transfer in meat during IRHAD will help to ascertain the suitability of using IRHAD to process biltong.

3. PROJECT PROPOSAL

The project proposal focuses on the drying kinetics and modelling of the heat and mass transfer in beef being processed into biltong using IRHAD. The study will also establish the quality of the resulting biltong.

3.1 Rationale for the Study

Biltong has a huge commercial potential for the domestic and export markets. Exploiting these opportunities require increased controlled production processes to assure consistency in the quality of the resultant biltong. Currently, there are no standard procedures and guidelines for biltong processing to ensure consistent quality and microbial safety of biltong. Drying methods such as IR drying provide possible alternatives to the conventional HAD of biltong. A combination of infrared heating and hot air drying offers plenty of advantages in terms of improved quality, enhanced microbial and fungal safety of the dried product plus savings on energy and time. Understanding the drying process of meat during biltong processing is necessary for assessing the suitability of alternative drying methods for biltong processing. There is no scientific literature on the modelling of heat and mass transfer in meat during biltong processing. Therefore, it is necessary to develop a heat and mass transfer model for the drying of meat being processed into biltong using IRHAD. Evaluating the drying kinetics of meat and the quality parameters of the resulting biltong is also critical in determining the suitability of using IRHAD for processing biltong.

3.2 Research Questions and Objectives

The research questions for this study are:

(i) What are the drying kinetics of beef undergoing IRHAD during biltong processing?

(ii) Which thin layer drying models are suitable for IRHAD of beef during biltong processing?

(iii) What are the mechanisms of heat and mass transfer in beef undergoing IRHAD during biltong processing?

(iv) What is the impact of IRHAD of beef on the quality of biltong?

The objectives of this study are to:

(i) evaluate the drying kinetics during IRHAD of beef being processed into biltong,
(ii) evaluate the suitability of selected thin layer drying models for simulating the IRHAD of beef being processed into biltong,
(iii) develop a 2D heat and mass transfer model for IRHAD of beef being processed into biltong, and
(iv) evaluate the quality of biltong produced using IRHAD.

3.3 Materials and Methods

3.3.1 The drying unit

The experiments will be performed using a cabinet dryer available at the Ukulinga Research Farm, University of KwaZulu-Natal (Pietermaritzburg, South Africa). The dryer was designed and constructed by CFW Projects (Pty) Ltd (Cape Town, South Africa). The drying cabinet is made of stainless steel and has a 100 mm thick thermal insulation. The dryer has two drying chambers arranged in series with regards to the direction of air flow. The chambers are of equal dimensions measuring 675 x 650 x 700 mm. Each chamber has a shelf with adjustable drying trays. The shelf in each chamber is attached to a set of three load cells (Revere Transducers Model SHB-0.05t-C3, Revere Transducers Europe, B.V, Breda, Netherlands) to record the remaining mass of samples being dried. Figure 3.1 is a schematic of the dryer's drying cabinet. Detailed illustrations and technical drawing of the drying unit are provided in the Figures 5.1 – 5.4 in Appendix A.

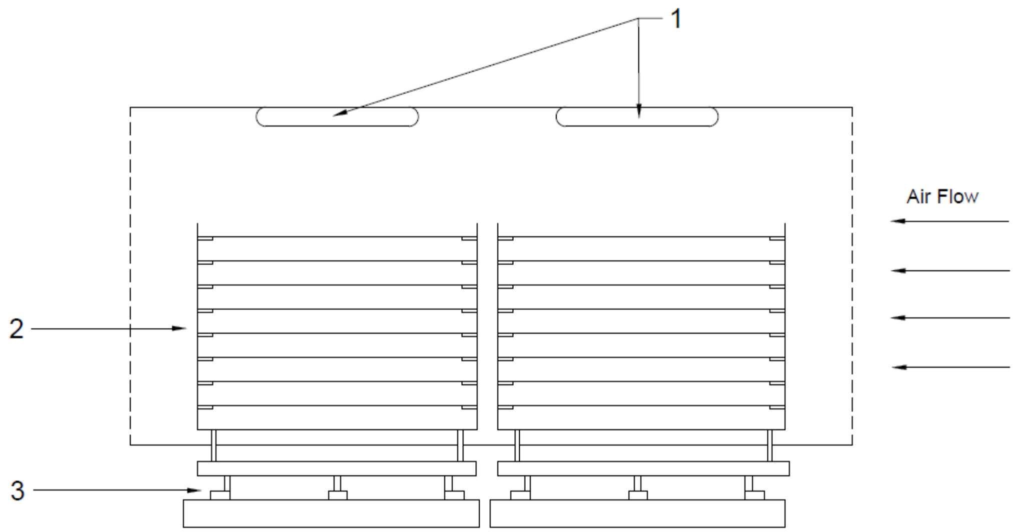

Figure 3.1 Schematic of the drying cabinet; 1 = IR halogen lamp heaters, 2 = Scaled shelving, 3 = Loads cells

The dryer is equipped with a pack of heating elements to heat the drying air. The relative humidity of the drying air is regulated using a Carel humiSteam x-plus humidifier (Carel Industries S.p.A, Padova, Italy). The dryer has a set of fans (intake, recirculation, and discharge) which are used to regulate the movement of air in the drying chamber. The drying air temperature and relative humidity are measured using T-type thermocouples (Pt100, Pentronic AB, Gunnebo, Sweden) and a Carel humidity sensor (DPDC111000 humidity sensor, Carel Industries S.p.A, Padova, Italy), respectively. The air velocity at the inlet and outlet of the drying cabinet is measured using an omnidirectional hot wire anemometer probe attached to an active air speed transmitter (HD 103T.0, Delta Ohm, Podova, Italy).

Currently, the dryer does not use IR heating. Hence, the dryer will be modified to incorporate IR heating. Infrared halogen lamps (Philips, tube type) with a power rating of 1000 W and dimensions of 6 and 355 mm in diameter and length respectively, will be attached on the top inside surface of each drying chamber (Figure 3.1). The infrared halogen lamp heaters emit IR radiation within the mid and far IR region (2.4 to 7 μm wavelength) (El-Mesery and Mwithiga, 2015). According to Pan and Atungulu (2011), the mid and far IR radiation is suitable for drying agricultural and food products. The IR heater will be set at a distance of 250 mm from the sample. The intensity of the infrared radiation will be regulated by using a voltage divider to vary the power of the IR lamps. The surface temperature of the IR heaters will be measured using a K-type thermocouple (Temperature Controls (Pty), Pinetown, South Africa) connected to a data logger (OM-DAQ-USB-2401, Omega, UK).

The drying data will be logged using a supervisory control and data acquisition (SCADA) system installed in the dryer. The SCADA system logs data on the remaining mass of product, air velocity, air flow rate, air temperature, and the relative humidity of the ambient, supply and return air. The control panel has a USB port through which the logged data can be exported using a USB memory stick.

3.3.2 Sample preparation

Beef carcasses will be procured from a local supermarket butchery (Pietermaritzburg, South Africa). The samples will be prepared from the loin region of the carcass. The cut will be made 20 mm from the carcass surface to ensure uniform moisture content in the samples (Trujillo *et al.*, 2003). The samples will be sliced along the muscle fibres to dimensions of 150 x 50 x 20 mm (Dzimba *et al.*, 2007). The initial moisture content, dimensions (length, width, and thickness), and colour of each sample will be determined, after which, the samples will be put in sealed polythene bags and stored in a refrigerator set at 4 ºC awaiting marination.

Biltong marinade will be made using salt and vinegar. The proportions of salt and vinegar will be expressed as a percentage of the mass of meat. The marinade will comprise of 2.5 % salt and 5 % brown spirit vinegar (Strydom and Zondagh, 2014; Jones, 2017). The beef samples will be retrieved from the refrigerator and placed in sterilised containers. The marinade will then be poured over the the beef and mixed manually until they are uniformly coated with marinade on all sides. The marinated samples will again be refrigerated at 4 ºC for 24 hours, during which time they will be turned every six hours. Thereafter, the samples will be retrieved from the refrigerator and left in the open for at least six hours to equilibrate to room temperature. The moisture content, dimensions (length, width, and thickness), and colour of the samples will be determined, once more, before drying (Cherono, 2014).

3.3.3 Drying experiments

Two sets of drying experiments, *viz.*, IRHAD and HAD of the pre-treated meat samples will be done.

a) Combined infrared and hot air drying (IRHAD)

The IRHA drying experiments will be done at IR power levels of 500, 750, and 1000 W; drying air temperature of 25, 30, and 35 ºC; drying air relative humidity of 30 and 50 %; and drying air velocity of 1.5 and 2.5 $m.s^{-1}$. The dryer will be preheated for at least one hour prior to the commencement of the experiments. Thereafter, a meat sample will be placed directly under the IR heater as shown in Figure 3.2. The mass of the sample will be measured using the load cells (Revere Transducers Model SHB-0.05t-C3, Revere Transducers Europe, B.V, Breda, Netherlands) attached to the drying shelf. The temperature of the sample will be measured using K-type thermocouples (Temperature Controls (Pty), Pinetown, South Africa). The thermocouples will be inserted in the meat sample at the specified locations (Figure 3.3). The thermocouples will be connected to a data logger (OM-DAQ-USB-2401, Omega, UK) to continuously measure and record the sample temperature throughout the drying process. The temperature, relative humidity, and velocity of the heated air, measured at the entrance and exit points, respectively, of the drying cabinet will be obtained from the dryer's SCADA system (§3.3.1). The meat sample will be dried until 50 % of the sample mass is lost (Jones, 2017). On completion of the drying test run, the sample will be cooled in a desiccator for 30 minutes and then packed in sealed polythene bags. Thereafter, the dried samples will be stored in a refrigerator set at 4 ºC awaiting further analysis.

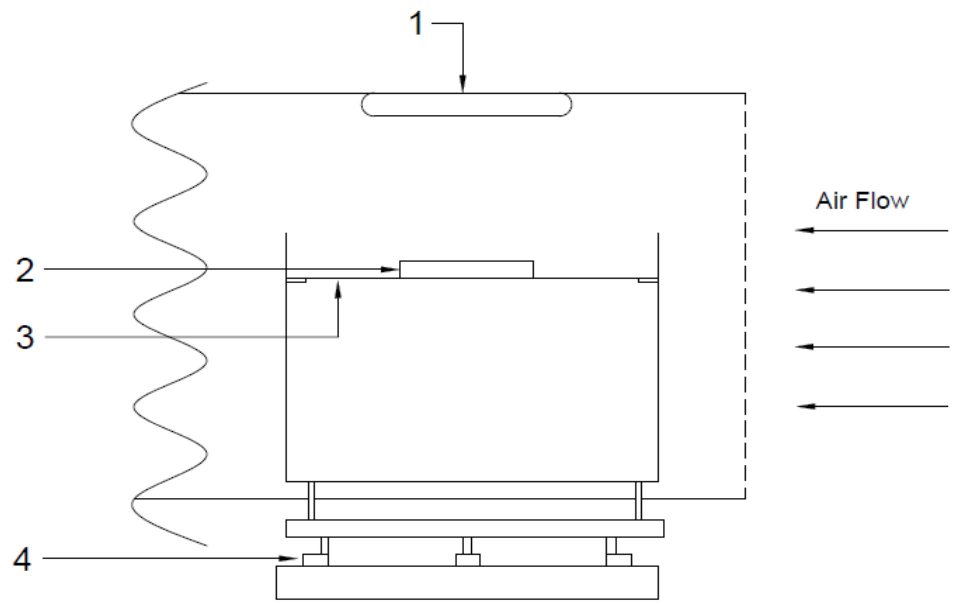

Figure 3.2 Set up of the drying experiment; 1 = IR halogen lamp heaters, 2 = Meat sample, 3 = Drying tray, 4 = Loads cells

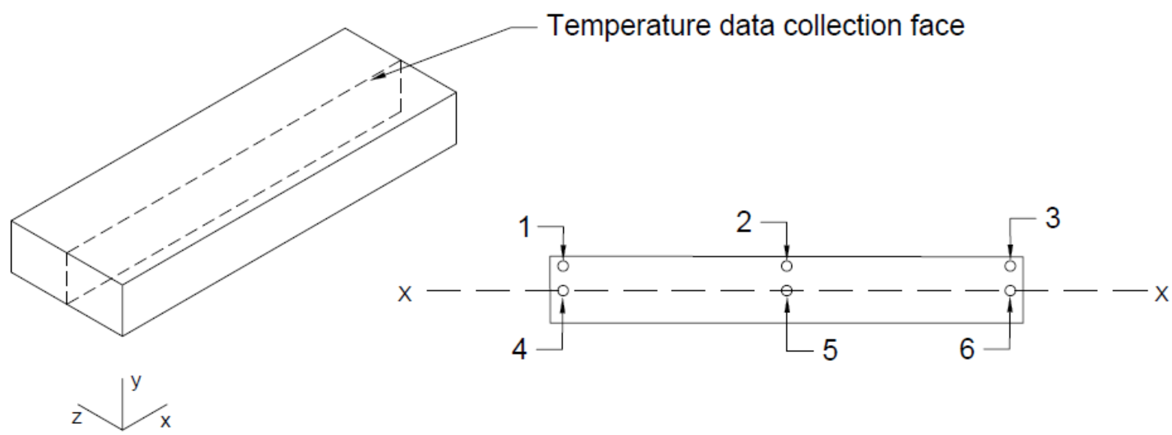

Figure 3.3 3D and 2D models of the meat sample showing the temperature data collection point; 1(20, 1), 2(75, 1), 3(130, 1), 4(20, 10), 5(75, 10), and 6(130, 10). X-X is the axis of symmetry**.**

b) Hot air drying (HAD)

The IR heater will be switched off in the HAD experiment. The drying air temperature, relative humidity and velocity will be set as described in §3.3.3(a). The mass and temperature of the meat sample will also be measure as described in §3.3.3(a). The meat sample will be dried until 50 %

of the sample mass is lost. After drying, the samples will be cooled in a desiccator for 30 minutes and then packed in sealed polythene bags. Thereafter, the dried samples will be stored in a refrigerator set at 4 ºC awaiting further analysis.

c) Experimental design

The experiment will employ a full factorial design comprising of four factors. The factors are drying method at four levels (HA, HA+IR (500 W), HA+IR (750 W), and HA+IR (1000 W)), drying air temperature at three levels (25, 30, and 35 °C), drying air relative humidity at two levels (30 and 50 %), and drying air velocity at two levels (1.5 and 2.5 $m.s^{-1}$) . Each treatment will have three replications (Figure 3.4). A total of one hundred and forty-four drying runs will be performed under this treatment structure.

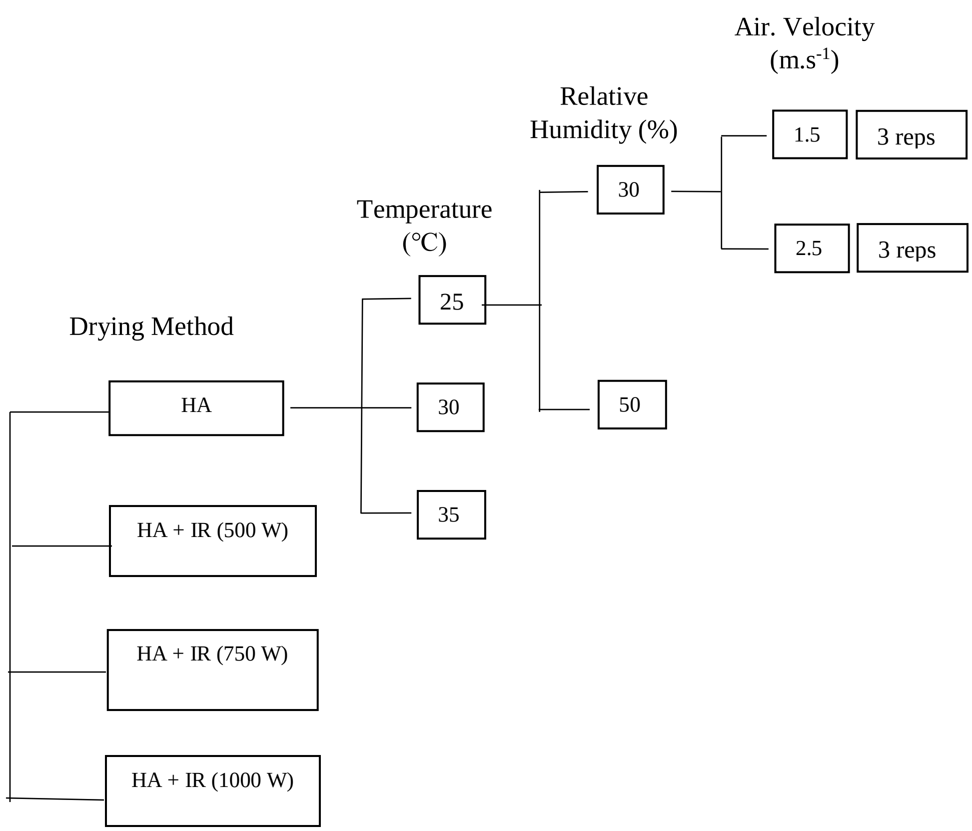

Figure 3.4 Experimental design

3.3.4 Evaluation of the drying kinetics

The drying curves will be obtained by plotting the moisture ratio (MR) vs drying time and the drying rate (D_R) vs drying time. The MR and D_R will be calculated using Equation 2.11 and Equation 3.1, respectively. The sample mass recorded during drying will be used to calculate the instantaneous moisture content (Appendix B1) that is necessary for calculating the MR and D_R.

$$D_R = \frac{M(t) - M(t + \triangle t)}{\triangle t} \tag{3.1}$$

Where:

M(t+△t) = moisture content of the sample at time t + △t (kg of water/kg of dry solid).

The effective moisture diffusivity will be determined from the solution of Fick's equation for an infinite slab as shown in Equation 2.10. Equation 2.10 is linearised as shown in Equation 3.2. The effective moisture diffusivity is then obtained from the slope of the graph of ln MR against drying time (Workneh and Muga, 2018).

$$\ln MR = \ln \frac{8}{\pi^2} - \left(\frac{\pi}{b}\right)^2 D_{eff} t \tag{3.2}$$

The activation energy (E_a) will be calculated from the Arrhenius type relationship between temperature and the effective moisture diffusivity, as shown in Equation 3.3 (Workneh and Muga, 2018).

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \tag{3.3}$$

Where:

D_0 = pre-exponential factor of Arrhenius equation equivalent to diffusivity at the maximum, temperature ($m^2.s^{-1}$),

R = universal gas constant ($kJ.ml^{-1}$), and

T = temperature in (° K).

Equation 3.3 is linearised (Equation 3.4) and the activation energy obtained from the slope of the graph of ln D_{eff} against $\left(-\frac{1}{RT}\right)$.

$$\ln D_{eff} = \left(-\frac{1}{RT}\right) E_a + \ln D_o \quad (3.4)$$

3.3.5 Thin layer modelling

The experimental data (MR and drying time) will be fitted to 8 thin layer drying models (Table 2.4, §2.5.3) using the non-linear least square analysis in MATLAB (MATLAB R18.2b, Mathworks, Inc., Natick, MA, USA). The models will be compared based on the coefficient of determination (R^2), the root mean square error (RMSE), and the sum of squares of errors (SSE). The best models will be chosen based on high R^2 and low values for RMSE and SSE.

3.3.6 Developing a heat and mass transfer model of a beef slice

A two-dimensional geometry of the meat sample will be used in the development of the heat and mass transfer model. In the dryer setup, heat is transferred to the beef sample through convection and radiation modes. Moisture is diffused from within the sample and lost to the surrounding air (Figure 3.5).

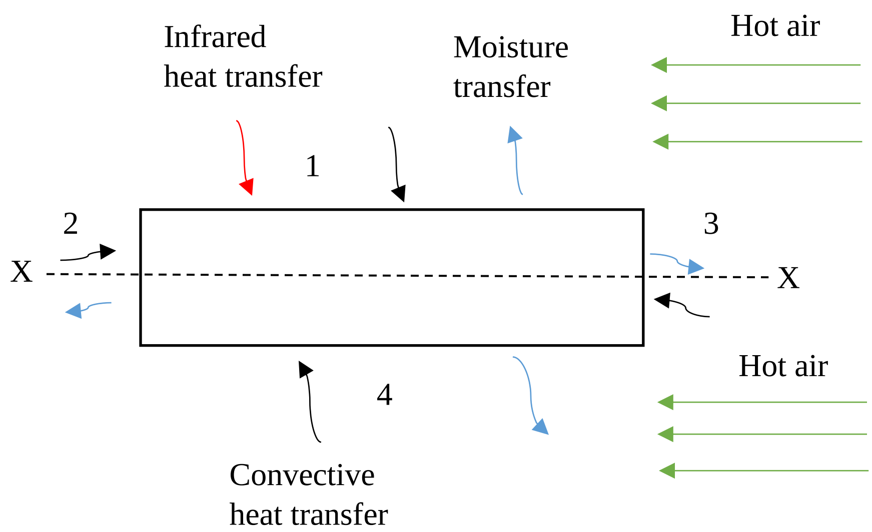

Figure 3.5 Simplified 2-dimensional model of the coupled heat and mass transfer

a) Governing equations for heat and mass transfer

The governing equations for the heat and mass transfer model are based on the principle of conservation of energy (Equation 2.1) and mass (Equation 2.3) as presented in § 2.5.2. The fluid velocity in Equation 2.1, is derived from Darcy's law of porous media given by Equation 3.5 (Datta, 2006; Feyissa *et al.*, 2009). Equation 3.5 accounts for the moisture transport due to the pressure gradient inside the product.

$$u = \frac{-K}{\mu} \nabla P \tag{3.5}$$

Where:

K = permeability of beef (m^2),

∇P = pressure gradient, and

μ = dynamic viscosity of water (Pa s).

The swelling pressure (P) in beef can be expressed in terms of the water content using Equation 3.6 (Van der Sman, 2007).

$$P = E(M - M_{eq}(T)) \tag{3.6}$$

Where:

$M_{eq}(T)$ = equilibrium water holding capacity of meat (kg of water/kg of sample), and

E = modulus of elasticity ($N.m^{-2}$).

Substituting Equation 3.6 into Equation 3.5 gives the expression of fluid velocity (Equation 3.7).

$$u = \frac{-KE}{\mu} \nabla (M - M_{eq}(T)) \tag{3.7}$$

The equivalent water holding capacity is determined by the empirical relationship in Equation 3.8 (Van der Sman, 2007).

$$M_{eq} = a_1 \frac{a_2}{(1 + a_3 \exp(-a_4 (T - T_\sigma)))} \tag{3.8}$$

Where:

T_σ = 52 °C is the centre of a logistic regression curve (water holding capacity vs temperature), and

$a_1 = 0.745$, $a_2 = 0.345$, $a_3 = 30$, and $a_4 = 0.25$ (Van der Sman, 2007).

The elastic modulus of meat changes with temperature (Tornberg, 2005). Feyissa *et al.* (2013) developed a logistic function (Equation 3.9) to describe the temperature dependent elastic modulus (E(T)) using data from Tornberg (2005).

$$E(T) = E_0 + \frac{E_m}{(1+\exp(-E_n(T-E_D))} \quad (3.9)$$

Where:

E_0 = elastic modulus of raw meat (minimum) = 12 kPa,

E_m = maximum elastic modulus = 83 kPa at T = 80 °C,

$E_n = 0.3$ and $E_D = 60$.

b) Boundary and initial conditions

No volumetric heating will be assumed. Thus, all the infrared energy is considered to be absorbed at the surface of the meat without penetration. Consequently, the total heat flux at the sample surface is a combination of convective and radiative heat flux (Pan *et al.*, 2014). The heat transfer at boundary 1 (Figure 3.5) is, therefore, given by Equation 3.10.

$$-n\left(k_p \nabla T + \rho_p c_{p,w} u T\right) = h(T_a - T) + \sigma(T_{IF}^4 - T^4) - h_{lv} h_m (M - M_a) \quad (3.10)$$

Where:

h = heat transfer coefficient ($W.m^{-2}.K^{-1}$),

T_a = drying air temperature (º K),

T_{IF} = emitter temperature (º K),

σ = Stefan-Boltzmann radiation constant,

h_m = mass transfer coefficient ($m.s^{-1}$),

h_{lv} = latent heat of evaporation ($J.kg^{-1}$), and

M_a = moisture concentration in air (kg of water/kg of air).

The heat transfer at boundaries 2, 3, and 4 (Figure 3.5) is given by Equation 3.11.

$$-n\left(k_p \nabla T + \rho_w c_{p,w} u T\right) = h(T_a - T) - h_{lv} h_m (M - M_a) \quad (3.11)$$

The mass transfer at boundaries 1, 2, 3, and 4 (Figure 3.5) is governed by Equation 3.12.

$$n(-D_{eff} \nabla M + uM) = h_m (M - M_a) \quad (3.12)$$

The moisture concentration in air (kg water/kg air) is determined from ideal gas laws as shown in Appendix B2.

The initial conditions will be set as follows:

$T = T_0$ and $M = M_0$ when $t = 0$;

c) Determination of heat and mass transfer coefficient

The convective heat transfer coefficients will be determined from the experiment data using the lumped analytical method as expressed in Equation 3.13 (Onwude *et al.*, 2018).

$$\frac{T - T_a}{T_0 - T_a} = \exp\left(-\left(\frac{hA_p}{\rho_p c_{p,p} V}\right)\right) \quad (3.13)$$

Where:

A_p = is the surface area of the sample (m^2), and

V = volume of the sample (m^3).

The convective heat transfer coefficient is estimated from the slope of the graph of $\ln\left(\frac{T - T_a}{T_0 - T_a}\right)$ against drying time (t) (Equation 3.14).

$$\text{slope} = \frac{hA_p}{\rho_p c_{p,p} V} \quad (3.14)$$

The mass transfer coefficient (h_m) is analogous to heat transfer coefficient and can be evaluated using Equation 3.15 and 3.16 (Onwude *et al.*, 2018).

$$h_m = \frac{h}{\rho_a c_{p,a} (Le)^{2/3}} \quad (3.15)$$

$$Le = \frac{\alpha_a}{D_a} \quad (3.16)$$

Where:

c_{pa} is the specific heat of air,

ρ_a = density of air ($kg.m^{-3}$),

Le = Lewis number

α_a = thermal diffusivity of air, and

D_a = mass diffusivity of air-vapour.

d) Thermophysical properties of meat

The density and heat capacity of meat will be evaluated from the composition of meat as outlined in Rao *et al.* (2014) (Appendix B3).

3.3.7 Simulation of the heat and mass transfer model of beef

The simulations will be performed using ANSYS® (ANSYS 19.2, ANSYS, Inc., Canonsburg, Pennsylvania USA). The governing mathematical model; Equations 2.1 and 2.3, the initial and boundary conditions, and the constitutive equations; will be solved based on finite element analysis. The meat sample will be modelled as a 2D configuration (Figure 3.3). The 2D geometry will be built using ANSYS designmodeller. The geometry will be meshed, followed by a mesh sensitivity analysis to check the quality of the mesh (Kumar and Dilber, 2007). The generated mesh will be refined at the boundaries to improve the accuracy of the numerical results. The simulations will be performed for all the treatments outlined in the experimental design (§ 3.3.3).

3.3.8 Validation of the heat and mass transfer model

The simulated results of temperature and moisture content will be compared to a new set of experimental data obtained as outlined in §3.3.3. The accuracy of the model will be judged based on the R^2, RMSE, and SSE.

3.3.9 Quality analysis of biltong

The dried samples (§3.3.3) will be retrieved from cold storage for quality analysis. The samples will be left in the open to acclimatise to room temperature, after which they will be analysed to determine the nutritional and physical quality parameters as shown in Table 3.2.

Table 3.1 Quality analysis of biltong

Component	Method	Reference
Moisture content	Oven drying	AOAC (2012)
Protein	Khedjel method	AOAC (2012)
Fat	Soxhlet extraction	AOAC (2012)
Fibre	Hydrolysis method	AOAC (2012)
Colour	Colorimeter	AMSA (2012)
Texture – Puncture test	Instron textural analyser	Cherono *et al.* (2016)
Texture profile analysis	Stable microsystems texture analyser	
Rehydration characteristics	Soaking	Nathakaranakule *et al.* (2007)
Shrinkage	Linear measurements	Feyissa *et al.* (2013)
Microstructure	Scanning electron microscopy	Fazaeli *et al.* (2012)

3.4 Expected Outputs

Some of the expected research outputs include;

(i) Review paper on modelling of heat and mass transfer during drying of beef,

(ii) Drying kinetics and thin layer modelling of IRHAD of beef being processed into biltong (Research paper),

(iii) Modelling the heat and mass transfer during HAD of beef for biltong production (Research paper),

(iv) Modelling the heat and mass transfer during IRHAD of beef for biltong production (Research paper),
(v) Quality parameters of biltong produced using IRHAD (Research paper), and
(vi) PhD thesis.

3.5 Resource Requirements

The resources needed to actualize this research are listed in Table 3.3.

Table 3.2 Resources needed for the research

Resources	Availability
Hot air tray dryer	Bioresources Engineering lab (Ukulinga)
Combined infrared and hot air dryer	Hot air tray dryer to be modified (Ukulinga)
Infrared halogen lamp heaters	To be purchased
Hot air oven dryer	Bioresources Engineering and Food laboratory
Digital balance	Bioresources Engineering and Food laboratory
Infrared intensity meter	To be purchase
Watt meter	To be purchase
Voltage regulator	To be purchase
Thermocouples	Bioresources Engineering
Data logger	Bioresources Engineering
Digital veneer callipers	Bioresources Engineering lab (Ukulinga)
Humidity and air velocity sensors	Bioresources Engineering
ANSYS® Fluent software	School of Engineering
MATLAB	School of Engineering
Instron texture analyser	Bioresources Engineering and Food laboratory
Stable microsystem texture analyser	Bioresources Engineering and Food laboratory
Hunterlab colorimeter	Bioresources Engineering and Food laboratory
Water bath	Bioresources Engineering and Food laboratory
Scanning electron microscope	Microscopy Unit (UKZN)

3.6 Budget

The budget for the proposed research is as shown in Table 3.4.

Table 3.3 Research budget

Item description	Unit	Quantity	Unit Price (Rands)	Total Cost (Rands)
Beef	kg	60	100	6000
Knife	No.	2	250	500
Salt	kg	5	10	50
Brown spirit vinegar	Litre	5	20	100
Polythene bags	Packet	2	150	300
Plastic containers	Piece	10	20	200
K-Type Thermocouple	Piece	8	400	3200
IR lamps	Piece	2	3500	7000
IR intensity meter	Piece	1	2000	2000
Voltage regulator	Piece	1	1000	1000
Watt metre	Piece	1	1000	1000
Gloves	Packets	2	150	300
Lab coat	Piece	2	100	200
Spectroscopy Lab fees	Annual	2	1000	2000
Total				23850

3.7 Work Plan

The research work plan is as shown by the ghant chat in Figure 3.6.

Milestone	2018			2019				2020			
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Literature review											
Project proposal											
Heat and Mass Transfer Model formulation											
Implementation of Heat and Mass Transfer Model in ANSYS Fluent											
Heat and Mass Transfer simulations											
HAD experiments											
Modification of hot air dryer by adding IR heaters											
IRHAD experiments											
Quality analysis											
Drying Kinetics											
Thin layer modelling											
Heat and Mass Transfer Model validation											
Thesis write-up											
Thesis submission											

Figure 3.6 Research work plan

4. REFERENCES

Abong'o, BO and Momba, MN. 2009. Prevalence and characterization of Escherichia coli O157: H7 isolates from meat and meat products sold in Amathole District, Eastern Cape Province of South Africa. *Food microbiology* 26 (2): 173-176.

Abukhalifeh, H, Dhib, R and Fayed, M. 2005. Model predictive control of an infrared-convective dryer. *Drying technology* 23 (3): 497-511.

Adler-Nissen, J. 2007. Continuous wok-frying of vegetables: Process parameters influencing scale up and product quality. *Journal of food engineering* 83 (1): 54-60.

Afzal, T, Abe, T and Hikida, Y. 1999. Energy and quality aspects during combined FIR-convection drying of barley. *Journal of food engineering* 42 (4): 177-182.

Ahmat, T, Barka, M, Aregba, AW and Bruneau, D. 2015. Convective drying kinetics of fresh beef: An experimental and modeling approach. *Journal of food processing and preservation* 39 (6): 2581-2595.

Allotey, J, Gashe, BA, Coetzee, SH, Mpuchane, S, Khonga, EB, Matsheka, MI and Murindamombe, G. 2014. Microbial quality assessment and predominant microorganism of biltong produced in butcheries in Gaborone, Botswana.

AMSA. 2012. *AMSA Meat colour measurement guide*. Champaign, Illinois.

AOAC. 2012. *Official Methods of Analysis of AOAC International*. AOAC International, Gaithersburg, USA.

Arntfield, S, Scanlon, M, Malcolmson, L, Watts, B, Cenkowski, S, Ryland, D and Savoie, V. 2001. Reduction in lentil cooking time using micronization: comparison of 2 micronization temperatures. *Journal of Food Science* 66 (3): 500-505.

Arsoy, S. 2008. Temperature-controlled infrared drying characteristics of soils. *Drying Technology* 26 (12): 1477-1483.

ASHRAE. 2009. *ASHRAE Handbook-Fundamentals*. American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., Atlanta.

Attwell, E. 2003. Biltong wakes up. *Food Reviews* 30 (2): 11-13.

Banout, J, Kucerova, I and Marek, S. 2012. Using a double-pass solar drier for jerky drying. *Energy Procedia* 30 738-744.

Bari, ML, Nei, D, Sotome, I, Nishina, I, Isobe, S and Kawamoto, S. 2009. Effectiveness of sanitizers, dry heat, hot water, and gas catalytic infrared heat treatments to inactivate Salmonella on almonds. *Foodborne pathogens and disease* 6 (8): 953-958.

Basman, A and Yalcin, S. 2011. Quick-boiling noodle production by using infrared drying. *Journal of Food Engineering* 106 (3): 245-252.

Bellagha, S, Sahli, A, Farhat, A, Kechaou, N and Glenza, A. 2007. Studies on salting and drying of sardine (Sardinella aurita): Experimental kinetics and modeling. *Journal of Food Engineering* 78 (3): 947-952.

Bird, R, Sterwart, W and Lightfoot, E. 2001. *Transport phenomena*. John Wiley and Sons Inc., New York.

Brewer, M. 2014. Chemical and physical characteristics of meat| Water-holding capacity. In: eds. Dikeman, M and Devine, C, *Encyclopedia of meat sciences*. Oxford: Academic Press, London.

Brooker, DB, Bakker-Arkema, FW and Hall, CW. 1992. *Drying and storage of grains and oilseeds*. Springer Science & Business Media,

Bualuang, O, Tirawanichakul, Y and Tirawanichakul, S. 2013. Comparative study between hot air and infrared drying of parboiled rice: Kinetics and qualities aspects. *Journal of Food Processing and Preservation* 37 (6): 1119-1132.

Burfoot, D, Everis, L, Mulvey, L, Wood, A and Campden, R. 2010. Literature review of microbiological hazards associated with biltong and similar dried meat products. *Food Standard Agency, London* 87

Burgheimer, FSM and Nelson, AI. 1971. Effect of near infrared energy on rate of freeze drying of beef spectral distribution. . *Journal of Food Science* 36 (1): 273–276.

Burnham, GM, Hanson, DJ, Koshick, CM and Ingham, SC. 2008. Death of Salmonella serovars, Escherichia coli O157: H7, Staphylococcus aureus and Listeria monocytogenes during the drying of meat: a case study using biltong and droëwors. *Journal of food safety* 28 (2): 198-209.
Celma, AR, Rojas, S and Lopez-Rodriguez, F. 2008. Mathematical modelling of thin-layer infrared drying of wet olive husk. *Chemical Engineering and Processing: Process Intensification* 47 (9-10): 1810-1818.
Chabbouh, M, Hajji, W, Hadj Ahmed, SB, Farhat, A, Bellagha, S and Sahli, A. 2011. Combined effects of osmotic dehydration and convective air drying on kaddid meats: Kinetics and quality. *Drying Technology* 29 (13): 1571-1579.
Chen, D, Li, K and Zhu, X. 2012. Determination of effective moisture diffusivity and activation energy for drying of powdered peanut shell under isothermal conditions. *BioResources* 7 (3): 3670-3678.
Chen, Q, Bi, J, Wu, X, Yi, J, Zhou, L and Zhou, Y. 2015. Drying kinetics and quality attributes of jujube (Zizyphus jujuba Miller) slices dried by hot-air and short-and medium-wave infrared radiation. *LWT-Food Science and Technology* 64 (2): 759-766.
Cheng, Q and Sun, D-W. 2008. Factors affecting the water holding capacity of red meat products: a review of recent research advances. *Critical reviews in food science and nutrition* 48 (2): 137-159.
Cherono, K. 2014. Infrared Drying of Biltong. Unpublished MSc thesis, Bioresources Engineering, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
Cherono, K, Mwithiga, G and Schmidt, S. 2016. Infrared drying as a potential alternative to convective drying for biltong production. *Italian journal of food safety* 5 (3):
Crank, J. 1979. *The mathematics of diffusion*. Oxford university press,
Dagerskog, M. 1979. Infrared radiation for food processing II. Calculationof heat penetration during infrared frying of meat products. *Lebensmittel Wissenschaft und Technologie* 12 (4): 252–257.
Datta, A. 2006. Hydraulic permeability of food tissues. *International Journal of Food Properties* 9 (4): 767-780.
Datta, A. 2007. Porous media approaches to studying simultaneous heat and mass transfer in food processes. II: Property data and representative results. *Journal of food engineering* 80 (1): 96-110.
Datta, A and Ni, H. 2002. Infrared and hot-air-assisted microwave heating of foods for control of surface moisture. *Journal of Food Engineering* 51 (4): 355-364.
Defraeye, T. 2014. Advanced computational modelling for drying processes–A review. *Applied Energy* 131 323-344.
Desmarchelier, P and Grau, F. 1997. Escherichia coli. In: eds. Hocking, A, Arnold, G, Jenson, I, Newton, K and Sutherland, P, *Foodborne microorganisms of public health importance*. AIFST (NSW Branch), Sydney, Australia.
Dhall, A, Datta, AK, Torrance, KE and Almeida, MF. 2009. Radiative heat exchange modeling inside an oven. *AIChE journal* 55 (9): 2448-2460.
Doymaz, I. 2014. Suitability of thin-layer drying models for infrared drying of peach slices. *Journal of food processing and preservation* 38 (6): 2232-2239.
Doymaz, İ. 2012. Infrared drying of sweet potato (Ipomoea batatas L.) slices. *Journal of food science and technology* 49 (6): 760-766.
Duan, Z-h, Jiang, L-n, Wang, J-l, Yu, X-y and Wang, T. 2011. Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. *Food and Bioproducts processing* 89 (4): 472-476.
Dzimba, FEJ, Faria, J and Walter, EHM. 2007. Testing the sensory acceptability of biltong formulated with different spices. *African Journal of Agricultural Research*
Ekechukwu, O. 1999. Review of solar-energy drying systems I: an overview of drying principles and theory. *Energy conversion and management* 40 (6): 593-613.

El-Mesery, HS and Mwithiga, G. 2015. Performance of a convective, infrared and combined infrared-convective heated conveyor-belt dryer. *Journal of food science and technology* 52 (5): 2721-2730.
Erbay, Z and Icier, F. 2010. A review of thin layer drying of foods: theory, modeling, and experimental results. *Critical reviews in food science and nutrition* 50 (5): 441-464.
Ertekin, C and Firat, MZ. 2017. A comprehensive review of thin-layer drying models used in agricultural products. *Critical reviews in food science and nutrition* 57 (4): 701-717.
Ertekin, C and Heybeli, N. 2014. Thin-layer infrared drying of mint leaves. *Journal of food processing and preservation* 38 (4): 1480-1490.
Eshtiagh, A and Zare, D. 2015. Modeling of thin layer hot air-infrared drying of green peas. *Agric Eng Int: CIGR Journal* 23 (4): 246-258.
Fasina, O, Tyler, B and Pickard, M.1997. Infrared heating of legume seeds effect on physical and mechanical properties. *Amer. Soc. Agric. Eng. Annual Meeting*,
Fasina, O, Tyler, R and Pickard, M. 1996. Effect of infrared heat treatment on the chemical composition and functionality of cereal grains-comparison of hulless and pearled barley. *Progress Report, Dept. of Applied Microbiology and Food Science, Univ. of Saskatchewan, Saskatoon*
Fazaeli, M, Tahmasebi, M and Djomeh, ZE. 2012. Characterization of food texture: application of Microscopic technology. *Current microscopy contributions to advances in science and technology* 2 (5): 855-871.
Feyissa, AH, Adler-Nissen, J and Gernaey, K.2009. Model of Heat and Mass Transfer with Moving Boundary during Roasting of Meat in Convection-Oven. *Excerpt from the Proceedings of the COMSOL Conference, Milan, Italy*,
Feyissa, AH, Gernaey, KV and Adler-Nissen, J. 2013. 3D modelling of coupled mass and heat transfer of a convection-oven roasting process. *Meat science* 93 (4): 810-820.
Gabel, MM, Pan, Z, Amaratunga, K, Harris, LJ and Thompson, JF. 2006. Catalytic infrared dehydration of onions. *Journal of Food Science* 71 (9): E351-E357.
Guizani, N, Al-Shoukri, AO, Mothershaw, A and Rahman, MS. 2008. Effects of salting and drying on shark (Carcharhinus sorrah) meat quality characteristics. *Drying technology* 26 (6): 705-713.
Gupta, T. 2001. Individual heat transfer modes during contact baking of Indian unleavened flat bread (chapati) in a continuous oven. *Journal of Food Engineering* 47 (4): 313-319.
Halder, A, Dhall, A and Datta, AK. 2011. Modeling transport in porous media with phase change: applications to food processing. *Journal of Heat Transfer* 133 (3): 031010.
Hamanaka, D, Uchino, T, Furuse, N, Han, W and Tanaka, S-i. 2006. Effect of the wavelength of infrared heaters on the inactivation of bacterial spores at various water activities. *International journal of food microbiology* 108 (2): 281-285.
Harmathy, T. 1969. Simultaneous moisture and heat transfer in porous systems with particular reference to drying. *Industrial & Engineering Chemistry Fundamentals* 8 (1): 92-103.
Hashimoto, A, Sawai, J, Igarashi, H and Shimizu, M. 1992. Effect of far-infrared irradiation on pasteurization of bacteria suspended in liquid medium below lethal temperature. *Journal of chemical engineering of Japan* 25 (3): 275-281.
Hebbar, HU, Vishwanathan, K and Ramesh, M. 2004. Development of combined infrared and hot air dryer for vegetables. *Journal of food engineering* 65 (4): 557-563.
Hii, C, Itam, C and Ong, S. 2014. Convective air drying of raw and cooked chicken meats. *Drying technology* 32 (11): 1304-1309.
Howell, JR, Menguc, MP and Siegel, R. 2015. *Thermal radiation heat transfer*. CRC press,
Huang, H, Lin, P and Zhou, W. 2007. Moisture transport and diffusive instability during bread baking. *SIAM Journal on Applied Mathematics* 68 (1): 222-238.
Huang, L. 2004. Infrared surface pasteurization of turkey frankfurters. *Innovative Food Science & Emerging Technologies* 5 (3): 345-351.
Huang, L and Sites, J. 2008. Elimination of Listeria monocytogenes on hotdogs by infrared surface treatment. *J. Food Sci.* 73 27-31.

Huang, T and Nip, W. 2001. Intermediate-moisture meat and dehydrated meat. *Meat science and applications* 403-442.
Hui, YH. 2012. *Handbook of meat and meat processing*. CRC press,
ICMSF. 1996. Bacillus cereus. In: ed. ICMSF, *Microorganisms in food 5: Microbiological specifications of food pathogens*. Blackie Academic and Professional London.
Islam, MR, Thaker, KS and Mujumdar, A. 2007. A diffusion model for a drum dryer subjected to conduction, convection, and radiant heat input. *Drying Technology* 25 (6): 1033-1043.
James, C, Lechevalier, V and Ketteringham, L. 2002. Surface pasteurisation of shell eggs. *Journal of Food Engineering* 53 (2): 193-197.
Jefferson, D, Lacey, A and Sadd, P. 2006. Understanding crust formation during baking. *Journal of Food Engineering* 75 (4): 515-521.
Ježek, D, Tripalo, B, Brnčić, M, Karlović, D, Rimac Brnčić, S, Vikić-Topić, D and Karlović, S. 2008. Dehydration of celery by infrared drying. *Croatica Chemica Acta* 81 (2): 325-331.
Johnson, J, Doyle, M, Cassens, R and Schoeni, J. 1988. Fate of Listeria monocytogenes in tissues of experimentally infected cattle and in hard salami. *Appl. Environ. Microbiol.* 54 (2): 497-501.
Jones, M. 2017. Profiling of traditional South African biltong in terms of processing, physicochemical properties and microbial stability during storage. Unpublished PhD thesis, Food Science, Stellenbosch University, Stellenbosch, South Africa.
Jones, M, Arnaud, E, Gouws, P and Hoffman, LC. 2017. Processing of South African biltong–A review. *South African Journal of Animal Science* 47 (6): 743-757.
Jun, S and Irudayaraj, J. 2003. A dynamic fungal inactivation approach using selective infrared heating. *Transactions of the ASAE* 46 (5): 1407.
Khir, R, Pan, Z, Salim, A, Hartsough, BR and Mohamed, S. 2011. Moisture diffusivity of rough rice under infrared radiation drying. *LWT-Food Science and Technology* 44 (4): 1126-1132.
Kocabiyik, H and Tezer, D. 2009. Drying of carrot slices using infrared radiation. *International journal of food science & technology* 44 (5): 953-959.
Kohashi, M, Akao, K-i and Watanabe, T. 1993. Non-thermal effects of a ceramics heater radiation on xanthine oxidase activity. *Bioscience, biotechnology, and biochemistry* 57 (12): 1999-2004.
Kondjoyan, A, Rouaud, O, McCann, M, Havet, M, Foster, A, Swain, M and Daudin, J. 2006. Modelling coupled heat–water transfers during a decontamination treatment of the surface of solid food products by a jet of hot air. I. Sensitivity analysis of the model and first validations of product surface temperature under constant air temperature conditions. *Journal of Food Engineering* 76 (1): 53-62.
Kouzeh-Kanani, M, Van Zuilichem, D, Roozen, J and Pilnik, W. 1982. A modified procedure for low temperature infrared radiation of soybeans. II. Inactivation of lipoxygenase and keeping quality of full-fat-flour. *Food Science and Technology= Lebensmittel-Wissenschaft und Technologie* 15 139-142.
Kowalski, SJ and Mierzwa, D. 2009. Convective drying in combination with microwave and IR drying for biological materials. *Drying Technology* 27 (12): 1292-1301.
Krishnamurthy, K, Jun, S, Irudayaraj, J and Demirci, A. 2008a. Efficacy of infrared heat treatment for inactivation of staphylococcus aureus in milk. *Journal of food process engineering* 31 (6): 798-816.
Krishnamurthy, K, Khurana, HK, Soojin, J, Irudayaraj, J and Demirci, A. 2008b. Infrared heating in food processing: an overview. *Comprehensive reviews in food science and food safety* 7 (1): 2-13.
Krishnamurthy, K, Tewari, JC, Irudayaraj, J and Demirci, A. 2010. Microscopic and spectroscopic evaluation of inactivation of Staphylococcus aureus by pulsed UV light and infrared heating. *Food and Bioprocess Technology* 3 (1): 93.
Kucerova, I, Hubackova, A, Rohlik, B-A and Banout, J. 2015. Mathematical modeling of thin-layer solar drying of Eland (Taurotragus oryx) Jerky. *International journal of food engineering* 11 (2): 229-242.

Kucuk, H, Midilli, A, Kilic, A and Dincer, I. 2014. A review on thin-layer drying-curve equations. *Drying Technology* 32 (7): 757-773.

Kumar, A and Dilber, I. 2007. *Fluid flow and its modeling using computational fluid dynamics*. CRC Press, Boca Raton,

Kumar, C, Joardder, M, Farrell, TW and Karim, M. 2016. Multiphase porous media model for intermittent microwave convective drying (IMCD) of food. *International Journal of Thermal Sciences* 104 304-314.

Kumar, C, Millar, GJ and Karim, M. 2015. Effective diffusivity and evaporative cooling in convective drying of food material. *Drying Technology* 33 (2): 227-237.

Kumar, DP, Hebbar, HU and Ramesh, M. 2006. Suitability of thin layer models for infrared–hot air-drying of onion slices. *LWT-Food Science and Technology* 39 (6): 700-705.

Kumar, PD, Umesh Hebbar, H, Sukumar, D and Ramesh, M. 2005. Infrared and hot-air drying of onions. *Journal of Food Processing and Preservation* 29 (2): 132-150.

Lado, B and Yousef, A. 2007. Characteristics of Listeria monocytogenes important to food processors. In: eds. Ryser, ET and Marth, EH, *Listeria, Listeriosis, and Food Safety, Third Edition*. CRC Press, Boca Raton.

Lawrie, R. 2017. The conversion of muscle to meat. In: ed. Toldra, F, *Lawrie's Meat Science*. Woodhead Publishing Ltd, Cambridge, UK.

Łechtańska, J, Szadzińska, J and Kowalski, S. 2015. Microwave-and infrared-assisted convective drying of green pepper: Quality and energy considerations. *Chemical Engineering and Processing: Process Intensification* 98 (2015): 155-164.

Leistner, L. 1987. Shelf-stable products and intermediate moisture foods based on meat. *Water activity: Theory and applications to food* 295-327.

Li, X. 2012. A study of infrared heating technology for tomato peeling: Process characterization and modeling. Unpublished thesis, University of California, Davis, California.

Li, X, Pan, Z, Upadhyaya, S, Atungulu, G and Delwiche, M. 2011. Three-dimensional geometric modeling of processing tomatoes. *Transactions of the ASABE* 54 (6): 2287-2296.

Li, X, Xie, X, Zhang, C-h, Zhen, S and Jia, W. 2018. Role of mid-and far-infrared for improving dehydration efficiency in beef jerky drying. *Drying Technology* 36 (3): 283-293.

Lin, Y-P, Lee, T-Y, Tsen, J-H and King, VA-E. 2007. Dehydration of yam slices using FIR-assisted freeze drying. *Journal of Food Engineering* 79 (4): 1295-1301.

Liu, Y, Zhu, W, Luo, L, Li, X and Yu, H. 2014. A mathematical model for vacuum far-infrared drying of potato slices. *Drying technology* 32 (2): 180-189.

Luikov, AV. 1975. Systems of differential equations of heat and mass transfer in capillary-porous bodies. *International Journal of Heat and mass transfer* 18 (1): 1-14.

Mayor, L and Sereno, A. 2004. Modelling shrinkage during convective drying of food materials: a review. *Journal of Food Engineering* 61 (3): 373-386.

Mhlambi, S, Naidoo, K and Lindsay, D. 2010. Enterotoxin-producing Staphylococcus strains associated with South African biltong at point of sale. *Journal of food safety* 30 (2): 307-317.

Miller, R. 2014. Chemical and physical characteristics of meat| Palatability. In: eds. Dikeman, M and Devine, C, *Encyclopedia of meat sciences*. Oxford: Academic Press, London.

Mondal, A and Datta, A. 2008. Bread baking–a review. *Journal of Food Engineering* 86 (4): 465-474.

Muriana, P, Gande, N, Robertson, W, Jordan, B and Mitra, S. 2004. Effect of prepackage and postpackage pasteurization on postprocess elimination of Listeria monocytogenes on deli turkey products. *Journal of food protection* 67 (11): 2472-2479.

Naidoo, K and Lindsay, D. 2010a. Pathogens associated with biltong product and their in vitro survival of hurdles used during production. *Food Protection Trends* 30 (9): 532-538.

Naidoo, K and Lindsay, D. 2010b. Survival of Listeria monocytogenes, and enterotoxin-producing Staphylococcus aureus and Staphylococcus pasteuri, during two types of biltong-manufacturing processes. *Food Control* 21 (7): 1042-1050.

Nasiroglu, S and Kocabiyik, H. 2009. Thin-layer infrared radiation drying of red pepper slices. *Journal of Food Process Engineering* 32 (1): 1-16.

Nathakaranakule, A, Jaiboon, P and Soponronnarit, S. 2010. Far-infrared radiation assisted drying of longan fruit. *Journal of Food Engineering* 100 (4): 662-668.

Nathakaranakule, A, Kraiwanichkul, W and Soponronnarit, S. 2007. Comparative study of different combined superheated-steam drying techniques for chicken meat. *Journal of Food Engineering* 80 (4): 1023-1030.

Nimmol, C, Devahastin, S, Swasdisevi, T and Soponronnarit, S.2005. Drying kinetics and quality of carrot dried by far-infrared radiation under vacuum condition. *International Agricultural Engineering Conference*,

Nortjé, K, Buys, E and Minnaar, A. 2005. Effect of γ-irradiation on the sensory quality of moist beef biltong. *Meat science* 71 (4): 603-611.

Onwude, DI, Hashim, N, Abdan, K, Janius, R, Chen, G and Kumar, C. 2018. Modelling of coupled heat and mass transfer for combined infrared and hot-air drying of sweet potato. *Journal of Food Engineering* 228 12-24.

Onwude, DI, Hashim, N and Chen, G. 2016. Recent advances of novel thermal combined hot air drying of agricultural crops. *Trends in Food Science & Technology* 57 132-145.

Osterhoff, D and Leistner, L. 1984. South African biltong--another close look. *Journal of the South African Veterinary Association* 55 (4): 201-202.

Özilgen, M and Özdemir, M. 2001. A review on grain and nut deterioration and design of the dryers for safe storage with special reference to Turkish hazelnuts. *Critical reviews in food science and nutrition* 41 (2): 95-132.

Palumbo, S, Komanowsky, M, Metzger, V and Smith, J. 1977. Kinetics of pepperoni drying. *Journal of Food Science* 42 (4): 1029-1033.

Pan, Z, Atungulu, G and Li, X. 2014. Infrared heating. In: ed. Sun, D-W, *Emerging technologies for food processing*. Elsevier.

Pan, Z and Atungulu, GG. 2010. Commercialization of food processing using infrared. In: eds. Doona, CJ, Kustin, K and Feehery, FE, *Case studies in novel food processing technologies: innovations in processing, packaging, and predictive modelling*. Woodhead Publishing Limited.

Pan, Z and Atungulu, GG. 2011. Combined infrared heating and freeze-drying. In: eds. Pan, Z and Atungulu, GG, *Infrared heating for food and agricultural processing*. CRC Press, Nwey York.

Pan, Z, Khir, R, Godfrey, LD, Lewis, R, Thompson, JF and Salim, A. 2008. Feasibility of simultaneous rough rice drying and disinfestations by infrared radiation heating and rice milling quality. *Journal of food engineering* 84 (3): 469-479.

Pawar, SB and Pratape, V. 2017. Fundamentals of infrared heating and its application in drying of food materials: a review. *Journal of food process engineering* 40 (1): e12308.

Petit, T, Caro, Y, Petit, A-S, Santchurn, SJ and Collignan, A. 2014. Physicochemical and microbiological characteristics of biltong, a traditional salted dried meat of South Africa. *Meat science* 96 (3): 1313-1317.

Petrova, I, Bantle, M and Eikevik, TM. 2015. Manufacture of dry-cured ham: A review. Part 2. Drying kinetics, modeling and equipment. *European Food Research and Technology* 241 (4): 447-458.

Podolak, R, Enache, E, Stone, W, Black, DG and Elliott, PH. 2010. Sources and risk factors for contamination, survival, persistence, and heat resistance of Salmonella in low-moisture foods. *Journal of food protection* 73 (10): 1919-1936.

Poligné, I, Collignan, A and Trystram, G. 2001. Characterization of traditional processing of pork meat into boucané. *Meat Science* 59 (4): 377-389.

Ponkham, K, Meeso, N, Soponronnarit, S and Siriamornpun, S. 2012. Modeling of combined far-infrared radiation and air drying of a ring shaped-pineapple with/without shrinkage. *Food and Bioproducts Processing* 90 (2): 155-164.

Prakash, B. 2011. Mathematical modeling of moisture movement within a rice kernel during convective and infrared drying. Unpublished thesis, University of California, Davis,

Prior, B. 1984. Role of micro-organisms in biltong flavour development. *Journal of Applied Bacteriology* 56 (1): 41-45.

Puente-Díaz, L, Ah-Hen, K, Vega-Gálvez, A, Lemus-Mondaca, R and Scala, KD. 2013. Combined infrared-convective drying of murta (Ugni molinae Turcz) berries: kinetic modeling and quality assessment. *Drying Technology* 31 (3): 329-338.
Purlis, E. 2010. Browning development in bakery products–A review. *Journal of Food Engineering* 99 (3): 239-249.
Ranjan, R, Irudayaraj, J and Jun, S. 2002. Simulation of infrared drying process. *Drying Technology* 20 (2): 363-379.
Rao, MA, Rizvi, SS, Datta, AK and Ahmed, J. 2014. *Engineering properties of foods*. CRC press,
Rastogi, NK. 2012. Recent trends and developments in infrared heating in food processing. *Critical reviews in food science and nutrition* 52 (9): 737-760.
Ratti, C. 2001. Hot air and freeze-drying of high-value foods: a review. *Journal of food engineering* 49 (4): 311-319.
Riadh, MH, Ahmad, SAB, Marhaban, MH and Soh, AC. 2015. Infrared heating in food drying: An overview. *Drying Technology* 33 (3): 322-335.
Rosenthal, I, Rosen, B and Bernstein, S. 1996. Surface pasteurization of cottage cheese. *Milchwissenschaft (Germany)*
Rudobashta, S, Zueva, G and Zuev, N. 2014. Mathematical modeling and numerical simulation of seeds drying under oscillating infrared irradiation. *Drying Technology* 32 (11): 1352-1359.
Sadin, R, Chegini, G-R and Khodadadi, M. 2014. Development and performance evaluation of a combined infrared and hot air dryer. *Journal of Biological and Environmental Sciences* 8 (22): 11-18.
Sadin, R, Chegini, G and Khodadadi, M. 2017. Drying characteristics and modeling of tomato thin layer drying in combined infrared-hot air dryer. *Agricultural Engineering International: CIGR Journal* 19 (1): 150-157.
Salagnac, P, Glouannec, P and Lecharpentier, D. 2004. Numerical modeling of heat and mass transfer in porous medium during combined hot air, infrared and microwaves drying. *International Journal of heat and mass transfer* 47 (19-20): 4479-4489.
Sawai, J, Fujisawa, M, Kokugan, T, Shimizu, M, Igarashi, H, Hashimoto, A and Kojima, H. 1997. Pasteurization of bacterial spores in liquid medium by far-infrared irradiation. *Journal of chemical engineering of Japan* 30 (1): 170-172.
Sawai, J, Isomura, Y, Honma, T and Kenmochi, H. 2006. Characteristics of the Inactivation of Escherichia coil by Infrared Irradiative Heating. *Biocontrol science* 11 (2): 85-90.
Sawai, J, Sagara, K, Hashimoto, A, Igarashi, H and Shimizu, M. 2003. Inactivation characteristics shown by enzymes and bacteria treated with far-infrared radiative heating. *International journal of food science & technology* 38 (6): 661-667.
Serra, X, Ruiz-Ramírez, J, Arnau, J and Gou, P. 2005. Texture parameters of dry-cured ham m. biceps femoris samples dried at different levels as a function of water activity and water content. *Meat Science* 69 (2): 249-254.
Sharma, G and Prasad, S. 2001. Drying of garlic (Allium sativum) cloves by microwave–hot air combination. *Journal of food engineering* 50 (2): 99-105.
Shilton, N, Mallikarjunan, P and Sheridan, P. 2002. Modeling of heat transfer and evaporative mass losses during the cooking of beef patties using far-infrared radiation. *Journal of Food Engineering* 55 (3): 217-222.
Soydan Karabacak, M, Esin, A and Cekmecelioglu, D. 2014. Drying behavior of meat samples at various fiber directions and air conditions. *Drying technology* 32 (6): 695-707.
Srikiatden, J and Roberts, JS. 2007. Moisture transfer in solid food materials: A review of mechanisms, models, and measurements. *International Journal of Food Properties* 10 (4): 739-777.
Stewart, C. 2003. Staphylococcus aureus and staphylococcal enterotoxins. In: ed. Hocking, A, *Foodborne microorganisms of public health significance*. Australian
Institute of Food Science and Technology (NSW Branch), Sydney.
Strydom, P and Zondagh, B. 2014. Biltong: A major South African ethnic meat product. *Encyclopaedia of meat sciences* 1 515-517.

Sui, Y, Yang, J, Ye, Q, Li, H and Wang, H. 2014. Infrared, convective, and sequential infrared and convective drying of wine grape pomace. *Drying Technology* 32 (6): 686-694.

Sumnu, SG and Sahin, S. 2008. *Food engineering aspects of baking sweet goods*. CRC Press,

Talla, A, Puiggali, J-R, Jomaa, W and Jannot, Y. 2004. Shrinkage and density evolution during drying of tropical fruits: application to banana. *Journal of Food Engineering* 64 (1): 103-109.

Tanaka, F and Uchino, T. 2010. Heat and Mass Transfer Modeling of Infrared Radiation for Heating. In: eds. Pan, Z and Atungulu, G, *Infrared Heating for Food and Agricultural Processing*, CRC Press.

Tanaka, F and Uchino, T. 2011. Heat and Mass Transfer Modeling of Infrared Radiation for Heating. In: eds. Pan, Z and Atungulu, G, *Infrared Heating for Food and Agricultural Processing*. CRC Press, New York.

Tanaka, F, Verboven, P, Scheerlinck, N, Morita, K, Iwasaki, K and Nicolai, B. 2007. Investigation of far infrared radiation heating as an alternative technique for surface decontamination of strawberry. *Journal of food engineering* 79 (2): 445-452.

Taylor, M. 1976. Changes in microbial flora during biltong production. *South African Food Review* 3 (2): 120-123.

Therdthai, N and Zhou, W. 2003. Recent advances in the studies of bread baking process and their impacts on the bread baking technology. *Food Science and Technology Research* 9 (3): 219-226.

Toldrá, F. 2010. *Handbook of meat processing*. John Wiley & Sons,

Tornberg, E. 2005. Effects of heat on meat proteins–Implications on structure and quality of meat products. *Meat science* 70 (3): 493-508.

Trujillo, FJ, Yeow, PC and Pham, QT. 2003. Moisture sorption isotherm of fresh lean beef and external beef fat. *Journal of food engineering* 60 (4): 357-366.

Van der Riet, W. 1976. Studies on the mycoflora of biltong. *S Afr Food Rev* 3 105.

Van der Riet, W. 1982. Biltong-A south-african dried meat product. *Fleischwirtschaft* 62 (8): 970-&.

Van der Sman, R. 2007. Soft condensed matter perspective on moisture transport in cooking meat. *AIChE Journal* 53 (11): 2986-2995.

Van Zuilichem, D, Van't Reit, K and Stolp, W. 1986. An overview of new infrared radiation processes for various agricultural products. *Food Engineering Process and Application* 1 595-610.

Wang, J and Sheng, K. 2004. Modeling of muti-layer far-infrared dryer. *Drying technology* 22 (4): 809-820.

Wang, L and Singh, R. 2004. Finite element modeling and sensitivity analysis of double-sided contact-heating of initially frozen hamburger patty. *Transactions of the ASAE* 47 (1): 147.

Wang, Y, Zhang, M, Mujumdar, AS and Chen, H. 2014. Drying and quality characteristics of shredded squid in an infrared-assisted convective dryer. *Drying technology* 32 (15): 1828-1839.

Wolter, H, Laing, E and Viljoen, BC. 2000. Isolation and identification of yeasts associated with intermediate moisture meats. *Food Technology and Biotechnology* 38 (1): 69-76.

Workneh, T and Muga, F. 2018. Microwave-assisted forced hot air circulation drying of thin-layer teff (Eragrostis tef). *Journal of Food, Agriculture & Environment* 16 (2): 34-42.

Yang, H, Sakai, N and Watanabe, M. 2001. Drying model with non-isotropic shrinkage deformation undergoing simultaneous heat and mass transfer. *Drying Technology* 19 (7): 1441-1460.

Yang, J, Bingol, G, Pan, Z, Brandl, MT, McHugh, TH and Wang, H. 2010. Infrared heating for dry-roasting and pasteurization of almonds. *Journal of Food Engineering* 101 (3): 273-280.

5. APPENDIX

5.1 Appendix A

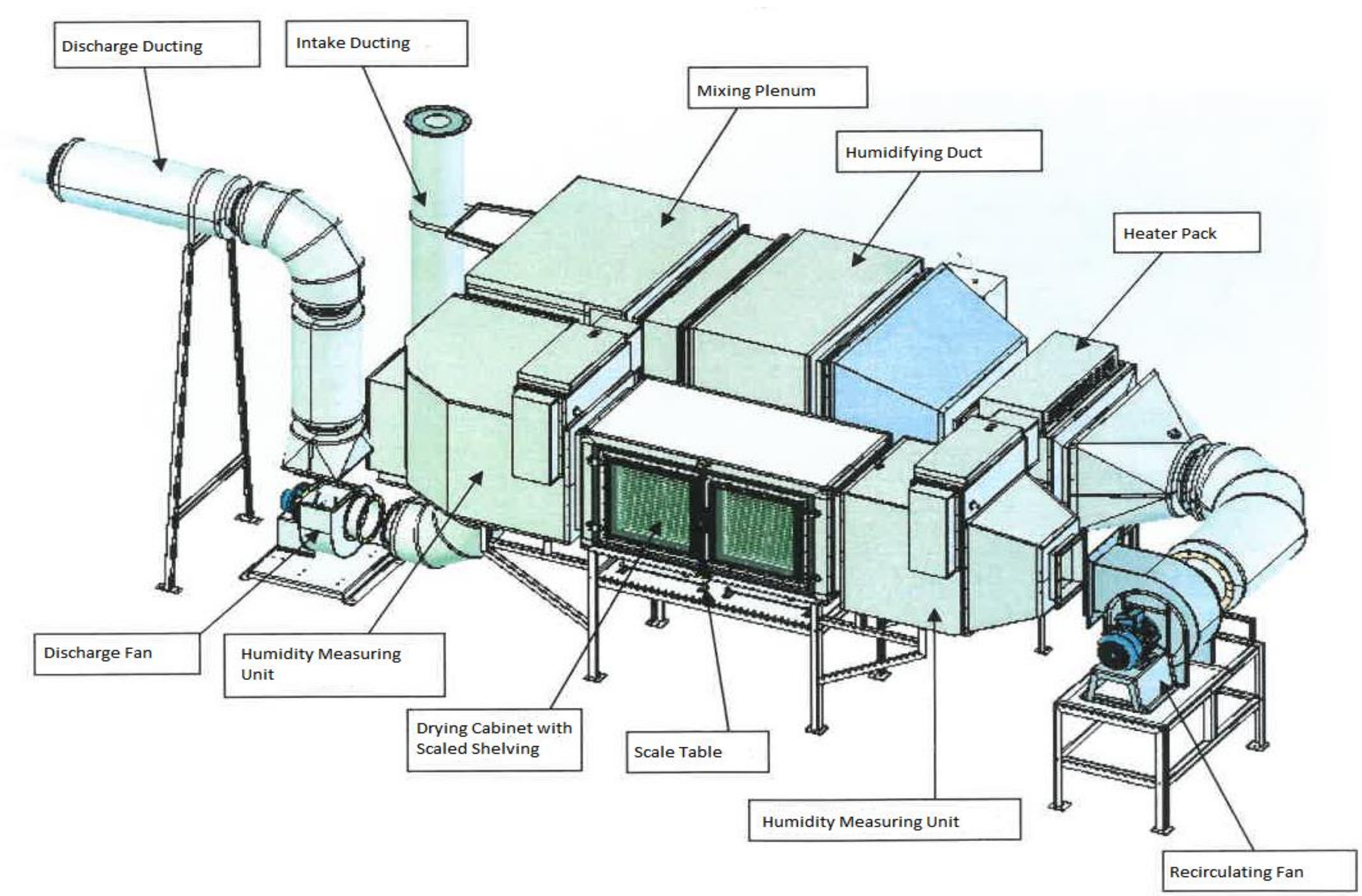

Figure 5.1 Layout of the laboratory drying unit

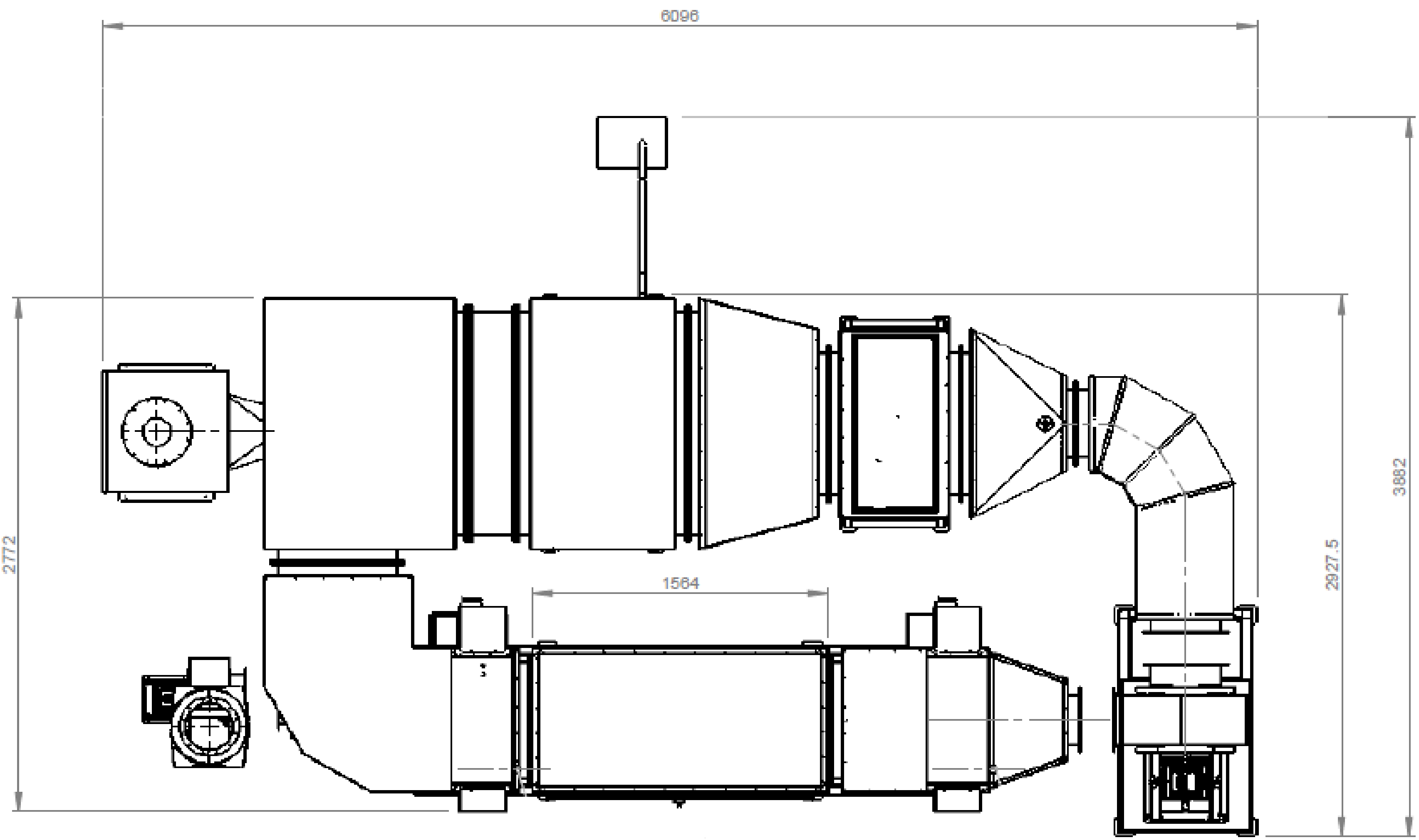

Figure 5.2 Top view of the laboratory drying unit

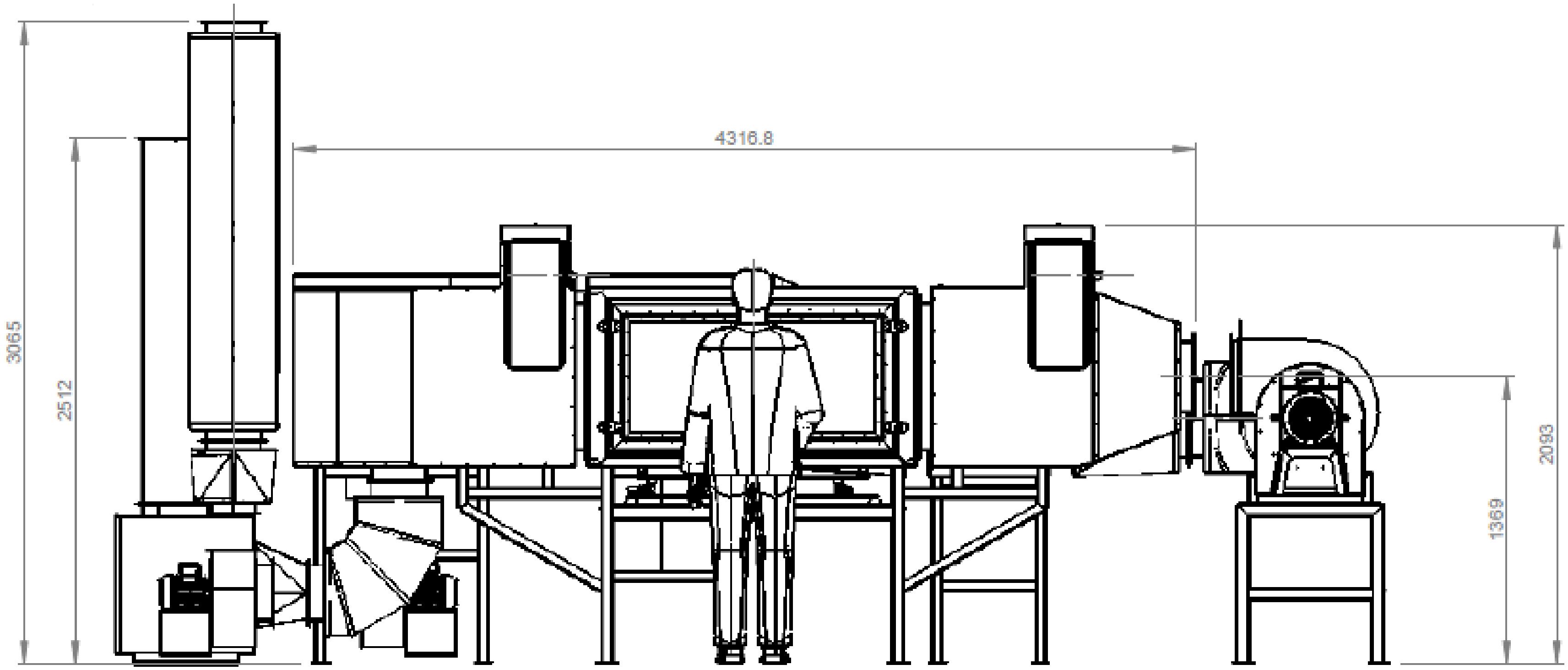

Figure 5.3 Front view of the laboratory drying unit

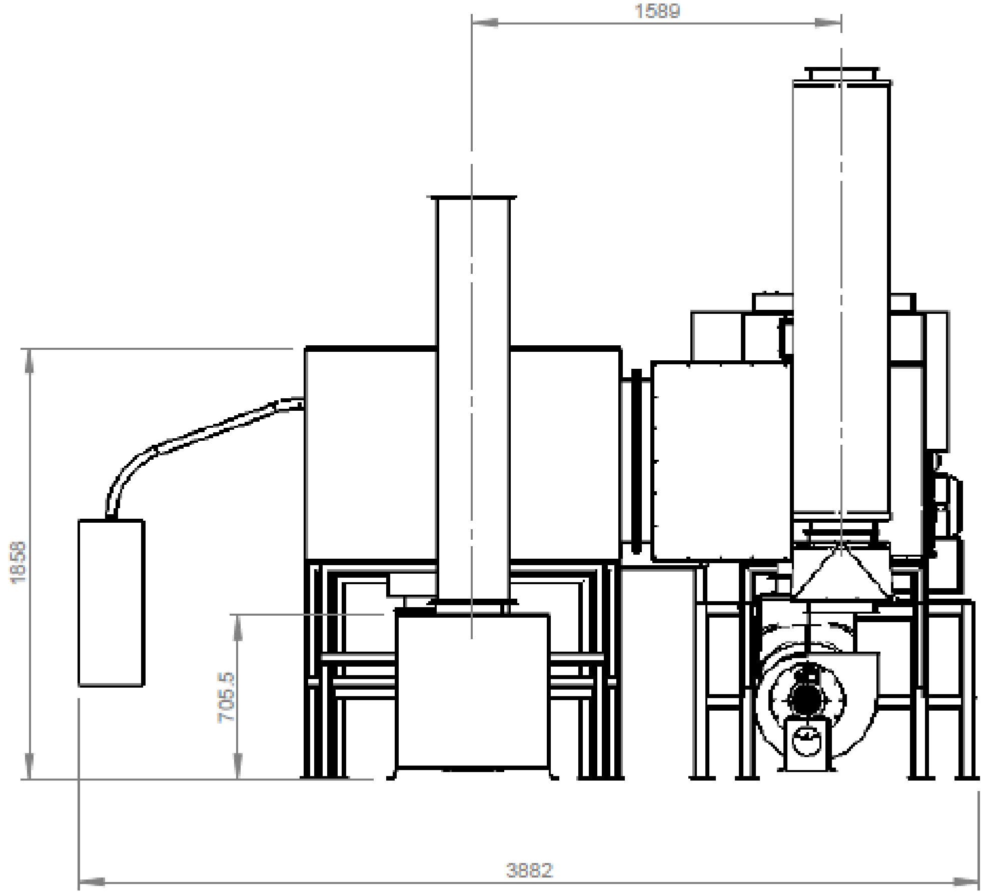

Figure 5.4 Left view of the laboratory drying unit

5.2 Appendix B

5.2.1 Appendix B1 Calculation of the instantaneous moisture content from the measured mass loss

$$Y_{w0} = \frac{m_{w0}}{m_0} \quad \text{(B1.1)}$$

$$m_w = m - (1 - Y_{w0})m_0 \quad \text{(B1.2)}$$

$$m_d = (1 - Y_{w0})m_0 \quad \text{(B1.3)}$$

$$X = \frac{m_w}{m_d} = \frac{m}{(1-Y_{w0})m_0} - 1 \quad \text{(B1.4)}$$

Where:

Y_{w0} = initial moisture content of the sample (kg of water/kg of sample),

m_{w0} = initial mass of water in the sample (kg),

m_0 = initial mass of the sample (kg),

m = instantaneous mass of sample (kg),

m_w = mass of water (kg),

m_d = mass of solid (kg), and

X = moisture content of sample expressed in dry basis (kg of water/kg of dry solid).

The wet basis moisture content (X_w) is calculated using Equation B1.5.

$$X_w = \frac{X}{X+1} \quad \text{(B1.5)}$$

5.2.2 Appendix B2 Calculation of the moisture concentration in air

$$X_{w,a} = \left(2.1667 \times 10^{-3} \times \frac{RH}{100} \times \frac{p_{vs}(T)}{T_a}\right) \times \frac{1}{\rho_a} \quad \text{(B2.1)}$$

Where:

X_{wa} = moisture fraction in air

RH = relative humidity,

ρ_a = density of air (kg.m^{-3}), and

p_{vs} = water vapour pressure (Pa), obtained from ASHRAE (2009) (Equation B2.2).

$$p_{vs} = \exp\left(\frac{-5.8\times10^3}{T_a} + 1.391 - 4.864\times10^{-2}T_a + 4.176\times10^{-5}T_a^2 - 1.445\times10^{-8}T_a^3 + 6.545\ln(T_a)\right) \quad \text{(B2.2)}$$

5.2.3 Appendix B3 Thermophysical properties of meat

Density $\rho = 1/\sum_i \frac{y_i}{\rho_i}$ (B3.1)

Specific heat capacity $c_p = \sum c_{pi} y_i$ (B3.2)

$c_{pi} = c_0 + c_1 T - c_2 T^2$ (B3.3)

Parallel model $k = \sum_i \frac{v_i}{k_i}$ (B3.4)

Perpendicular model $\frac{1}{k} = \sum_i \frac{v_i}{k_i}$ (B3.5)

Where:

v_i = volume fraction of each component,

y_i = mass fraction of each component, and

i = water, protein, carbohydrate, and fats.